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DYNAMO-ELECTRIC MACHINERY

A MANUAL
FOR STUDENTS OF ELECTROTECHNICS

BY

hillips)

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CHAPTER XVIII.

ARC-LIGHTING DYNAMOS.

In cases where lighting is to be done exclusively by arc lamps in great numbers, it is usual to arrange the lamps all *in series*, even to as many as 100 to 200 lights, and to provide a dynamo-machine which will give a constant, or nearly constant, current at a sufficiently high voltage. The usual current for which arc lamps are designed is ten amperes. Some lamps are designed, however, for 8 or 6 amperes, and some for 4 amperes. These are therefore exceptions. On the other hand, the arc lamps used for search-lights and lighthouse work are designed to take larger currents, up to 200 amperes or more. With continuous-currents arcs cannot be maintained burning steadily unless they are fed at a pressure of about 40 to 45 volts for each lamp. If the pressure is insufficient, the arcs will be unstable and give out a hissing sound. The steady arc behaves as though it exercised a counter electromotive-force of about 39 volts. When arc lamps are to be used *in parallel* with one another, the mains must have a greater difference of potential than 45 volts—55 or 60 volts is preferable—in order that additional resistances may be introduced to steady the current through each lamp. Such additional resistances are not necessary when a number of arc lamps are used *in series*, as they help to steady one another. The great advantage in the series arrangement is the saving in copper thereby effected. Alternate-current arcs only need a pressure of 30 to 33 virtual volts.

In arc-lighting in series, the function of the dynamo is to keep the amperes constant, no matter how many or few lamps are in circuit; whilst each lamp is provided with a shunt device which governs the movement of the carbons, so that the feeding of them shall keep the length of the arc, and the volts at the terminals of the lamp, approximately constant.

We may take it, therefore, that a system of 20 arcs in series will require a dynamo giving a current of, say, 10 amperes, and a pressure, when all the lamps are in use, of nearly 1000 volts. This allows 45 volts per lamp, and 5 volts more for driving the current through the resistance of the wires between each lamp and the next.

Constant-current dynamos are also needed for the purposes of municipal lighting by means of special glow-lamps (with thick carbon wires instead of thin filaments), connected in series, so that the same unvarying current flows successively through a large number of them.

It was suggested by Deprez in 1881, that by a species of compound winding, consisting of an initial excitation and a shunt excitation combined, a dynamo might be constructed to give a constant current at constant speed. The assumption which underlay his reasoning, that the magnetism is proportional to the exciting power, is, we know, not justified except for the early and unstable stage of magnetization; all attempts to produce a practical compound winding for this purpose have therefore failed.

For the production of constant currents at such high voltages as 2000 to 3000 volts the ordinary ring and drum armatures, wound in a closed coil, in numerous sections, and provided with a commutator consisting of numerous closely-packed parallel bars, have not been found entirely satisfactory, for the commutator of this type is liable to give way under the high pressure, and to deteriorate under the action of long sparks flashing over its surface from brush to brush under the wide alterations of lead that are inseparable with this mode of working. Nevertheless, good results have been obtained by several firms (see p. 465) in the use of high voltages in machines having ordinary commutators with many segments.

Experience, however, is in the main against the use of armatures of this type. More simple forms are needed that will not break down under the conditions of work. These forms are usually associated with other modes of construction in which the armature winding does not constitute a closed coil,

OPEN-COIL DYNAMOS.

As explained on p. 40, it is possible to construct armatures in which the separate coils or sections of the windings are not united together in one closed circuit. An example is given in Fig. 299. This diagram (which should be compared with Fig. 33, p. 39) shows an armature consisting of two separate loops, set in planes at right angles to one another, so that when one is passing through the inactive region the other is in the position of maximum action. There is no reason why these two loops should not have each a separate 2-part commutator like that of Fig. 24; and one pair of brushes might press on both commutators. It is, however, obviously more convenient to unite these two commutators into a single one of four parts, as in Fig. 299; and then it will at once be seen that as this rotates between its pair of brushes one loop only will be in action at once, the other loop being cut out of circuit for the time being. It would clearly be possible to arrange any number of loops or coils in this way so that only that loop or coil which was passing through the position of maximum action should be feeding the brushes, all the rest being meantime open-circuited. A ring armature wound in sections might of course be similarly arranged, so that the pairs of sections have each a separate commutator; and Fig. 300 (which should be compared with

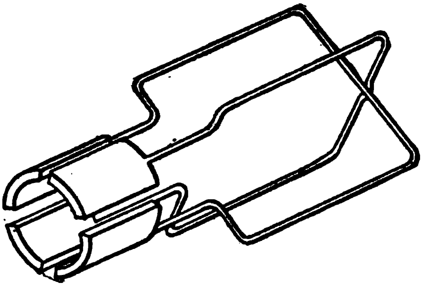


FIG. 299.
SIMPLE OPEN-COIL ARMATURE.

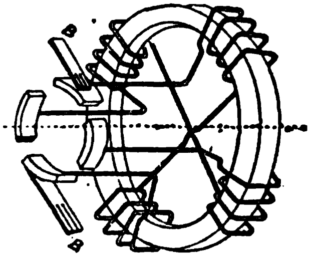


FIG. 300.—FOUR-PART OPEN-COIL RING ARMATURE.

Fig. 31, p. 88) shows such a ring, but with the two commutators cut down and formed into a 4-part collector.

It will be noticed that each coil is joined at the back to the one diametrically opposite to it, and that the front ends of the coils pass to the commutator. As a matter of fact, it would make no difference in either of these armatures were the wires which cross at the back all united where they meet.

It will be seen that the position of the brushes with respect to the position of maximum action will not be the same as in the case of a closed-coil winding. In a closed-coil winding the diameter of commutation is near the coils of minimum action. With open-coil armatures the current is led directly from the coils of maximum activity.

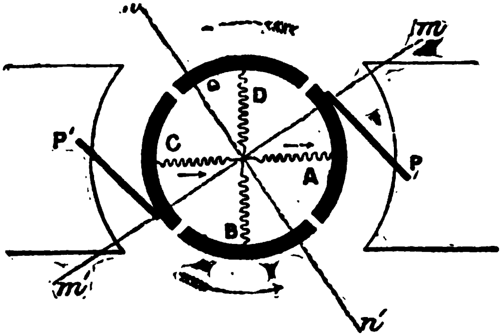


FIG. 301.—DIAGRAM OF OPEN-COIL ARMATURE.

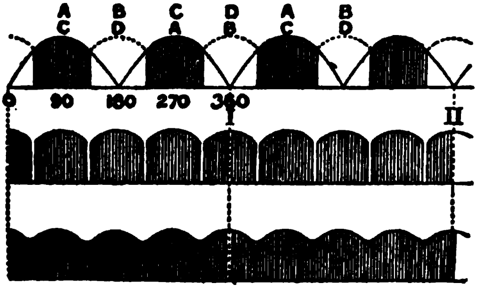
The current might be simultaneously collected from more than one coil at once, either (1) by making the pieces of the commutators overlap, or (2) by connecting to the brushes that touch on the line of maximum activity, another pair having either a forward or a backward lead. If we now consider Fig. 301 we shall see this a little more clearly. This figure is a diagram of such an armature, the coils or loops being here represented merely by wavy lines.

The wavy line A C may represent either a pair of coils such as there are in Fig. 300 on the ring, or may represent a single loop or group of windings round a drum. There is a pair of commutator-plates for A C, and another at right angles for B D. Coils A and C are just coming into the position of best action shown by the line *m m'*; they are delivering a current to the brushes P P, and this current will accordingly increase a little, and then decrease again. Meantime coils B and D are idle. If the four parts of the compound commutator each occupy just a quarter of the circumference, it is clear that when A comes into action its plane makes an angle of 45° with *m m'*, and that just as it leaves contact with the brush it makes again an angle of 45° on the other side, being in contact with all intermediate positions; and so with each coil as it passes the brushes. There will be a momentary break of current and a spark as the two successive segments pass under the brush, unless the brush touches both at once. Remembering that Fig. 29, p. 38, represents the alternating electromotive-force from a single loop or pair of coils, and that Fig. 30, p, 38, represents the same electromotive-force rectified by the use of a simple 2-part commutator, we shall be able to represent the effect of our new arrangement by some such diagram as Fig. 302. The angles marked below are reckoned from the neutral line *n n'*. When coil A has gone round 90° from this position, it is in the position of maximum induction: but because segment A of the commutator is itself 90° in breadth, the current will be collected from 45° to 135°. The shaded portions of the curve show the discontinuous effect due to the coils A and C coming into circuit during two quarters of the rotation. The coils B and D come in in the intervals as indicated by the dotted lines. The induced currents will therefore present an approximate continuity depending on the arrangements of the commutator and the brushes. Fig. 303 represents the effect if there were gaps between the segments and the commutator; and it will be noticed that the electromotive-forces, though all of the same sign, are discontinuous. If the brushes thus left contact with one segment of the commutator before the next come into contact there would inevitably be a considerable amount of sparking. Fig. 304 shows the result of making contact with one set before the other set is cut out; the induced electromotive-force being now continuous, but with undulating fluctuations of strength. During the time when both sets of coils are in contact with the brushes, they are, of course, in parallel with one another. During this stage of the action the resistance of the armature is half as great as when one of the coils is cut out; but it is necessary to cut out the idle coil, otherwise some of the current from the active coil would flow back uselessly through the idle coil that was in parallel with it. During the time when the two sets of coils are in parallel they are not equally active. The induced electromotive force is increasing in one and diminishing in the other; there is but a moment when they are equally active —when they make equal angles with *m m'*. At all other moments the higher electromotive-force of the more active coil tends to send a back-current through the less active coil. This is to a certain extent opposed to the self-induction of the less active coil, and if contact is broken just at the moment when the higher electromotive-force has reduced the current in the less active coil to zero, the commutation will be sparkless.

FIG. 302.

FIG. 303.

FIG. 304.



CURVES ILLUSTRATING THE PRODUCTION OF CURRENTS BY USING AN OPEN-COIL 4-PART ARMATURE.

From what has now been said, it will be clear that open-coil armatures may be constructed either as rings, drums, or disks. They may be arranged to run either in a simple or in a multiple magnetic field. The principal dynamos constructed upon this plan are the Brush machine and the Thomson-Houston machine; but there are a few others which also come within the category of open-coil dynamos.

Brush's Dynamo.—One of the best known of these machines is the Brush dynamo (Fig. 306). The magnet heads are insulated with sheets of the so-called vulcanized fibre, thoroughly varnished. The cores are, however, first surrounded with a thin sheet of copper, soldered together at the edges so as to form a continuous tube or envelope. The object of this copper coating is to deaden sudden vibrations of magnetism of the iron cores. Over the copper envelope are wound four or five thicknesses of very heavy paper saturated with shellac varnish to insulate the wire from the iron. In some of the Brush dynamos there is a double winding, a shunt or "teazer" circuit being added to maintain the magnetism of the field-magnets when the main current is opened. An automatic regulator, consisting of a carbon rheostat connected as a shunt to the magnet winding and operated by a solenoid in the main circuit, is applied to keeping the current constant (see p. 224, and Chapter XXIX.).

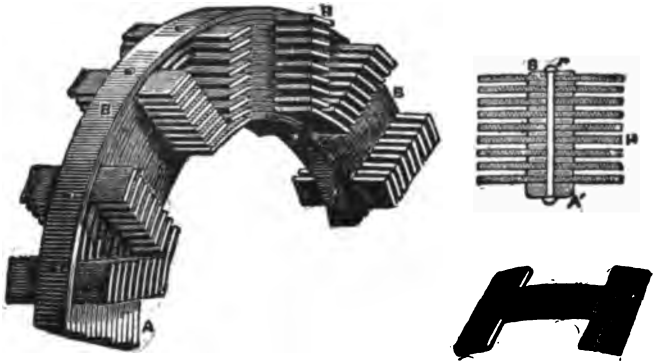


FIG. 305.—CORE OF BRUSH RING.

The armature has, like the Pacinotti ring, projecting teeth between the coils, but, unlike that early form of armature, the successive sections are not connected in a closed circuit.

The ring is built up of a thin iron ribbon 1·5 millimetres thick. Fig. 305 shows its construction, though in reality a larger number of pieces of thinner iron than is shown are used. The ribbon is wound upon a circular foundation ring

A′, projecting cross-pieces of the same thickness (marked H) being inserted at intervals to separate the convolutions, admit of ventilation, and form suitable projections between which to wind the coils. It is secured by well-insulated radial bolts. All iron parts which are to adjoin the wire of the "bobbins" are covered first with a layer of strong heavy canvas saturated with shellac varnish, and in the case of the armature of the larger machines there are additional layers of tough paper saturated with shellac varnish. A sheet of strong cotton cloth inserted occasionally separates contiguous layers of wire from each other both in the armature bobbins and in the coils of the field-magnets. All the bobbins are wound by hand, in the same direction, and the inner ends of diametrically opposite bobbins are soldered together, and carefully insulated from all other wires and adjacent metal. The free outer ends of each pair of bobbins are separately carried through a boring in the shaft, and connected to diametrically opposite segments of the commutator.

For each pair of coils there is a separate commutator. In the No. 8 L size of machine, which is depicted in Fig. 306 there are 12 coils on the armature, six commutators grouped in three pairs, and three sets of brushes. This size is commonly known as a "60-light" machine. Its electromotive-force at a speed of 800 revolutions per minute is 3000 volts.

In considering the method in which the coils are joined up to the commutator, we will take the case of an 8-coil armature with the commutators grouped in two pairs; it will then be easy to extend the method to the case of a twelve-coil machine.

Continuity is obtained in the currents by making the two parts of the commutator of each pair of coils overlap those of the commutator belonging to the pair of coils that is at right angles, one pair of brushes resting on both commutators. Fig. 307 is a diagram illustrating this device. Each pair of segments overlap the other to the extent of 45°. Each of the two pairs of coils is thus cut out twice during a revolution; it is twice in circuit alone, as when the brushes are at A A′, and four times in circuit along with the pair that are at

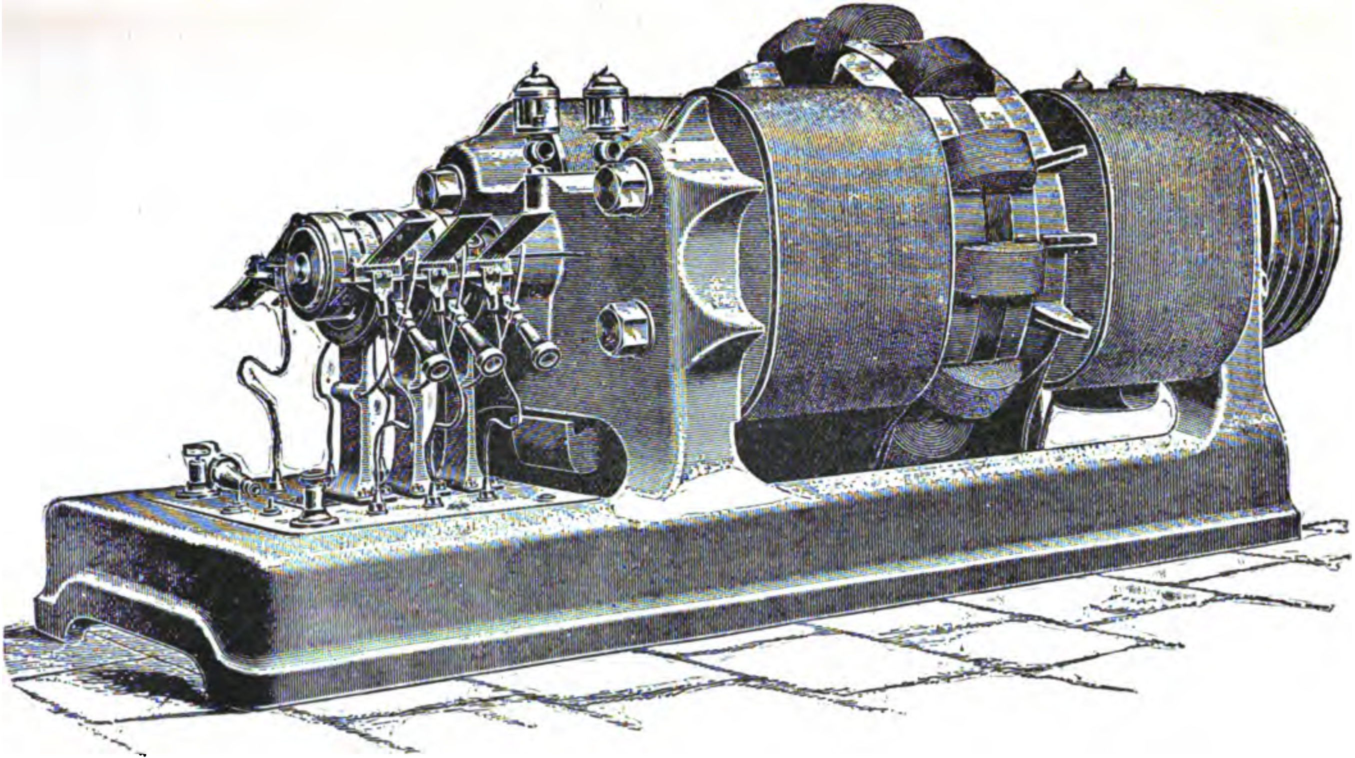


FIG. 306.—BRUSH ARC-LIGHT DYNAMO.

right angles, when the brushes are at B B′. Fig. 308 shows in perspective the commutator of an 8-coil Brush armature. There are really four commutators here, corresponding to the four pairs of coils, grouped in pairs; one pair of commutators being set one-eighth of a rotation (45°) in advance of the other. It will be seen from this figure that while the brushes A A′ (shown in dotted lines) are receiving current from *one pair* of coils only, the brushes B B′ are at the same instant receiving the current from *two pairs* of coils which are joined in parallel with one another in consequence of both of their commutators touching the same pair of brushes. The arrangement may be still further studied by the aid of Fig. 309, which also illustrates the way of connecting the brushes with the circuit. In this figure the eight coils are numbered as four pairs, and

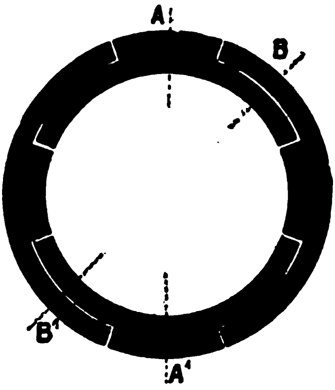


FIG. 307.—PAIR OF OVERLAPPING COMMUTATORS.

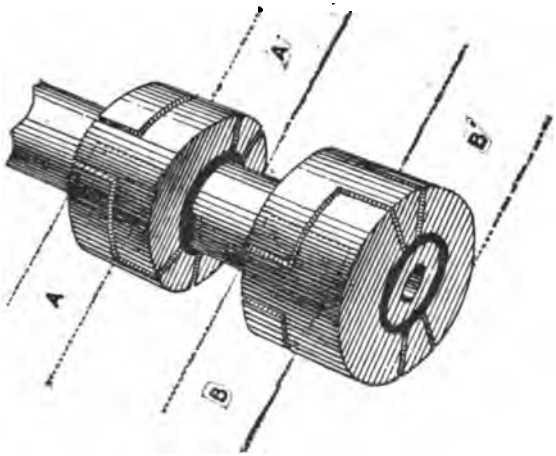


FIG. 308.—BRUSH COMMUTATOR FOR ARMATURE WOUND WITH FOUR PAIRS OF COILS.

each pair has its own commutator, to which pass the outer ends of the wire of each coil, the inner ends of the two coils being united across to each other (not shown in the diagram). In the actual machine, each pair of coils, as it passes through the position of least action (i. e. a position somewhat past the vertical dotted line midway between the poles (Fig. 309), and when the number of magnetic lines passing through it is a *maximum*, and the rate of change of these magnetic lines a *minimum*) is cut out of connection. This is accomplished by causing the two halves of the commutator to be separated from one another by about one-eighth of the circumference at each side. In the figure it will be seen that the coils marked 1, 1, are "cut out." Neither of the two halves of the commutator touches the brushes. In this position, however, the coils 3, 3, at right angles to 1, 1, are in the position of best action, and the current powerfully induced in them flows out of the brush marked A (which is, therefore, the negative brush) into that marked A′. This brush is connected across to the brush marked B, where the current re-enters the armature. Now, the coils 2, 2 have just left the position of best action, and the coils 4, 4 are beginning to approach that position. In both these pairs of coils, therefore, there will be a rather

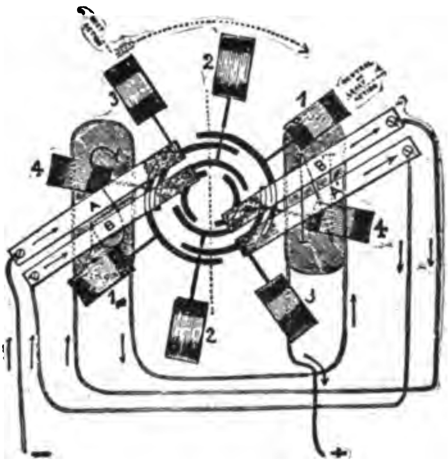


FIG. 309.—CONNECTIONS OF BRUSH DYNAMO.

weaker electromotive-force. The current on passing into B splits, part going through coils 2, 2, and part through 4, 4, and reuniting at the brush B′, whence the current flows round the coils of the field-magnets to excite them, and then round the external circuit, and back to the brush A.

Thus the coils in which there is a maximum electromotive-force are joined in series with coils in which the electromotive-force is weaker, though by a method different from that employed in a closed winding armature. As the armature rotates, coils 4, 4 come to the position of maximum electromotive-force, and they are then in series with coils 1, 1 and 3, 3, so that the electromotive-force of the machine varies very little with the change of the position of the coils. In some machines it is arranged that the current shall go round the field-magnets, after leaving brush A′, and before entering brush B.

The following table summarizes the successive order of connections during a half-revolution:—

First position. (Coils 1, 1 cut out.)

$A - 3 - A'$; $B\left\langle\begin{matrix}4\\2\end{matrix}\right\rangle B'$; Field magnets – External circuit – A,

Second position. (Coils 2, 2 cut out.)

$A\left\langle\begin{matrix}1\\3\end{matrix}\right\rangle A'$; $B - 4 - B'$; Field magnets – External circuit – A,

Third position. (Coils 3, 3 cut out.)

$A - 1 - A'$; $B\left\langle\begin{matrix}2\\4\end{matrix}\right\rangle B'$; Field magnets – External circuit – A,

Fourth position. (Coils 4, 4 cut out.)

$A\left\langle\begin{matrix}3\\1\end{matrix}\right\rangle A'$; $B - 2 - B'$; Field magnets – External circuit – A.

By rocking the brushes by means of the appliance provided for that purpose (see Fig. 306), a point can be found at which the sparking is reduced to a minimum (see p. 450).

From the foregoing considerations, it will be clear that the four pairs of coils in the Brush machine really constitute four separate machines, each delivering alternate currents to a commutator, which commutes them to intermittent unidirectional currents in the brushes; and that these independent machines are ingeniously united in pairs by the device of letting one pair of brushes press against the commutators of two pairs of coils. Further, that these paired machines are then connected in series, by bringing a connection round from brush A′ to brush B.

In the 12-coil machine (Fig. 306) there are three pairs of commutators, the segments of each pair are joined to four coils at right angles to each other, and the pairs are mounted on the shaft so that the first pair joined to coils 1, 4, 7 and 10 having a lead of 30° in advance of the second pair jointed to coils 2, 5, 8 and 11, and the third pair joined to coils 3, 6, 9 and 12 have a lag of 30° behind the second pair. The way the brushes are connected up in series is shown in Fig. 310.

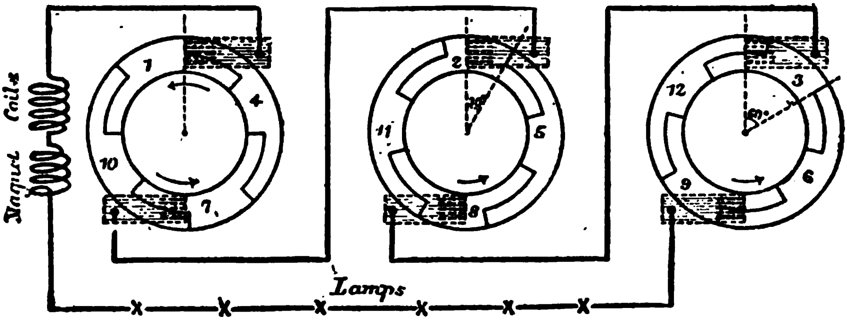


FIG. 310.—CONNECTIONS OF A 12-COIL BRUSH DYNAMO.

Multipolar Brush machines are now made to be driven direct from the engine shaft. At the station of the Mutual Electric Light and Power Co., Chicago, there are three machines driven direct by Willans engines at 500 revolutions per minute. Each machine is capable of lighting 125 arc lamps in series. The automatic regulator regulates so closely that any number of these lamps may be thrown off and on with impunity. The armature of these machines is 39 inches in diameter and has 24 coils, that is six sets of four coils each. All the coils in any one set are in the same position relatively to the four poles, and are joined in series just as two coils are joined in series in a 2-pole machine. The connections to the commutators are on exactly the same principle as in the case of the 12-coil armature considered above, with this modification, that a difference of position of 45° on the armature corresponds to a difference of 90° in the 2-pole machine. Each of the three portions of the commutator, therefore, consists of eight sections, instead of four sections; the sections that are diametrically opposite being interconnected.

Some elaborate tests on Brush dynamos, with two different patterns of armature, were made[1] in 1889 by Mr. Murray of Melbourne. These showed commercial efficiencies of about 69·8 per cent. in machines with core-plates 0·05 inches thick and of about 78 per cent. in those with core-plates 0·022 inch thick. The value of B attained were about 4800 in field-magnet cores and 27,000 in the armature cores. The fluctuations of the current were about 1·5 per cent.

For further tests see Thurston in *Journal of Franklin Institute*, Sept. 1886. Consult also a small volume, "Electrical Engineers' and Students' Chart and Handbook of the Brush Arc Light System," by H. C. Reagan, jun. (New York, 1895).

Thomson-Houston Dynamo.—This machine, which is equally remarkable, was designed by Professor Elihu Thomson of Lynn and Edwin J. Houston of Philadelphia. It is unique in having a spherical armature with a 3-part commutator revolving between the cup-shaped poles of an introverted field-magnet. As will be seen from Fig. 311, the field-magnet core consists of two flanged iron tubes furnished at their inner ends with hollow cups cast in one with the tubes, and accurately turned to receive the armature. Upon the tubes are wound the coils C C′, and afterwards the two parts are united by means of a number of wrought-iron bars *b b*, which constitute the yoke of the magnet and at the same time protect the coils. The magnets are carried on a framework, which also supports the bearings for the armature shaft X. The original form of the armature, shown in Fig. 311, had a very remarkable winding. There were but three coils. The inner ends of these were united together *and not connected to any other conductor.* The three wires were then wound over an iron shell in three sets of windings making 120° with one another, and arranged to be at equal average distances from the core, while their overlapping made the external form nearly spherical. The new ring armature, Fig. 312, has six groups of coils arranged in three pairs. The three pairs are

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[1] *Journal Inst. Electrical Engineers*, xvii. 710, Nov. 1889.

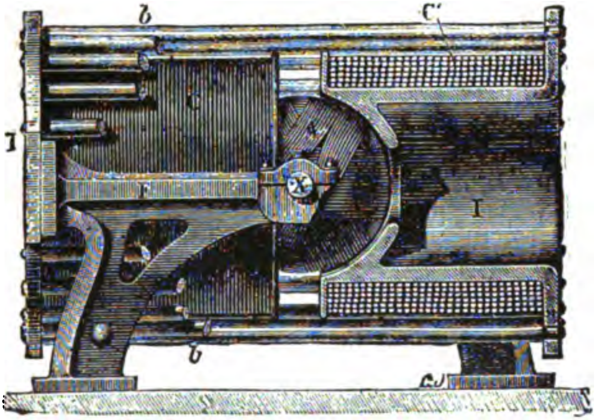


Fig. 311.—Thomson-Houston Arc-light Dynamo.

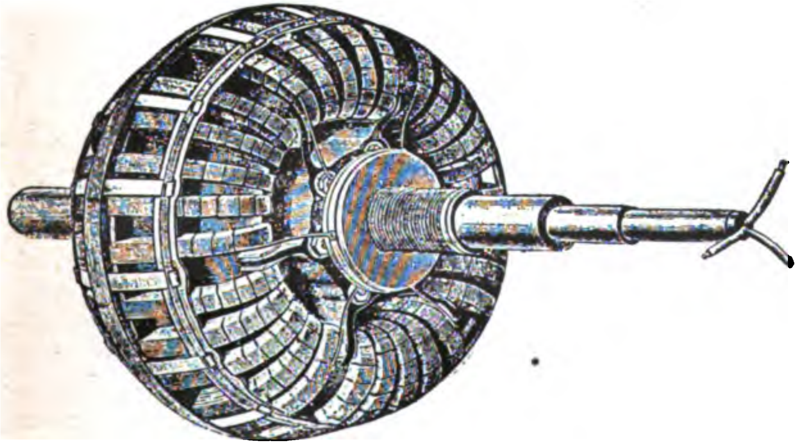


Fig. 312.—Ring Armature of Thomson-Houston Dynamo.

themselves connected star-wise, having a common junction for three of their ends, the three other ends of the wires being brought down through the hollow shaft, and joined to the three segments of the commutator. The coils are replaceable singly.

When this armature is rotated within the cavity between the cup-shaped poles alternate currents are generated in each coil in turn, and it now remains to consider how these alternate inductions are rectified and combined by the commutator. In the diagrams which follow, the rotation is represented as left-handed, as viewed from the commutator-end of the shaft, as it is in practice. Fig. 313 represents the arrangement in diagram. The three coils represented diagrammatically by

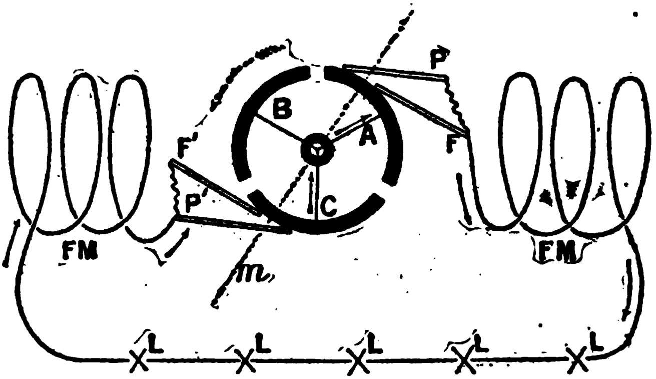


FIG. 313.—COMMUTATOR AND CIRCUIT OF THOMSON-HOUSTON DYNAMO.

the three lines A B C, are united at their inner extremities, each outer end being led to one segment of a 3-part commutator. There are two positive brushes P and F, and two negative brushes P′ and F′. The current delivered to P and F first flows round one of the field-magnets, thence goes to the outer circuit of lamps, returning through the other field-magnet to P′ and F′. The reader should compare this diagram with Fig. 309, and note that in that figure the neutral line divides the armature obliquely into two halves, the induced currents flowing outwardly from centre to commutator in all coils that are rising through the right-hand half of this obliquely divided circle; and inwardly from commutator to centre in all coils descending through the left-hand half of the rotation. Accordingly, in Fig. 313, in which the neutral line is at right angles to $m m'$, there will be an outward current in A and an inward one in C; B being for the moment cut out of circuit as it passes through the neutral position. Continuity is obtained by the device mentioned on p. 448, of having the second pair of brushes F F′ following the pair P P′, In this position of the armature A and C make about equal angles with the line of maximum action $m m'$, hence the two electromotive forces in these coils are for the moment about equal, but that in A is increasing, that in C decreasing. As these coils are now in series, their separate electromotive-forces are of course added together. A moment later A will be in the position of maximum induction; C will be rapidly approaching the neutral position and B will again begin to have electromotive-force induced in it. B and C will for the moment be in parallel with one another and in series with A. Then C comes to the neutral position and is cut out of circuit, while A and B are in series, and so forth.

If the width of the gaps between the segments of the commutator be equal to the width between the adjacent brushes, each coil will be out of circuit whenever it is more than 60° from the position of maximum action, and the time during which any two coils are in parallel will be practically nil. But if the brushes F F′ follow at a considerable angle—about 60° in practice—behind the brushes P P′, there will be considerable duration of the stage during which two coils are in parallel.

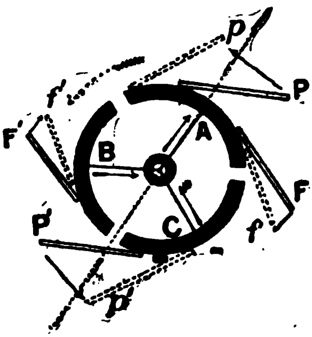
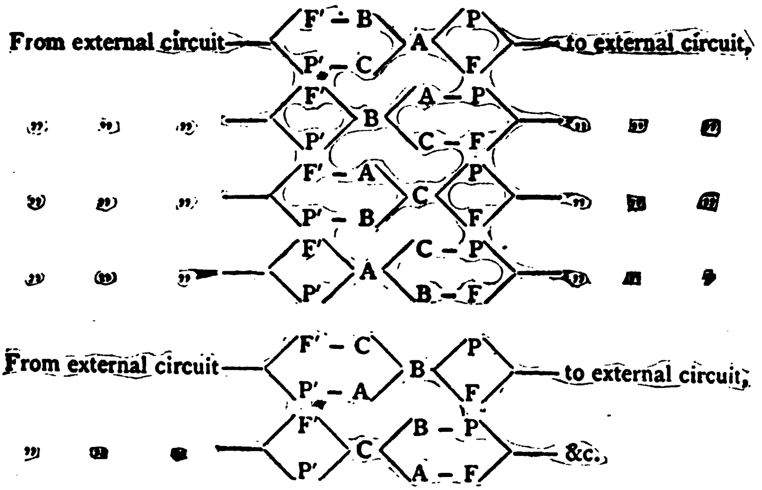


FIG. 314.—COMMUTATING POSITIONS.

The regulation of this machine to maintain a constant current is accomplished by an automatic shifting of the brushes. The actual method now used is termed "backward" regulation. The pair of "following" brushes F F′ is shifted backwards to *ff′* as shown in Fig. 314, whilst at the same time the leading brushes P P′ are shifted forward through an angle one-third as great towards *p p′*. If, as stated above, the brushes are 60° apart under normal conditions, there will be exactly 120° on either side between the positive brushes P F and the negative brushes P′ F′; and as 120° is the exact length of each segment of the commutator, no coil will be cut out, and parallelism will subsist between two coils through angles of 60°: that is to say, there will always be two of the three coils in parallel with one another and in series with the third coil. The six stages of change will be :—



Now suppose the current to become too strong owing to reduction of number of lamps in circuit, the "following" brushes are made to recede. This will shorten the time during which any single coil in passing through the maximum position is throwing its whole electromotive-force into the circuit, and will hasten the moment when it is put in parallel with a comparatively idle coil. During such movements of regulation the whole machine is momentarily short-circuited six times during each revolution by F receding so far towards P′, and F′ receding so far towards P, as that both touch the same segment of the commutator at one instant. The action is assisted by the slight advance of P and P′, but the main object of this advance is to lessen the sparking. If the current is too weak, then the pairs of brushes must be made to close up, thereby reducing the time during which the most active coils are in parallel with those that are less active.

Regulating Gear.—This motion of advance and retreat is accomplished by the simple link-gear not shown in any of the figures. The automatic movement is imparted by the regulating electromagnet R (Fig. 815), whose pole, of paraboloidal form, attracts its armature according to the current flowing round it, and raises the arm A. The circuits which operate this mechanism are also shown. Normally the electromagnet R is short-circuited through a bye-pass circuit, and only acts when this circuit is opened. At some convenient point of the main circuit two solenoids are introduced, their cores being supported by a spring; and the yoke of the cores operates the contact lever S. If the current becomes too strong this contact is opened, and the regulating magnet R raises the arm A. During running the lever S is continually vibrating up and down, and so altering the brushes to the requirements of the circuit. A carbon shunt of high resistance *r* is added to minimize the destructive spark at S. It might be expected that with only three parts to the commutator, the sparks occurring as the segments pass under the brushes would speedily destroy the surface. This difficulty has been met by Prof. Thomson in the boldest manner. By means of a small mechanical blower, fixed upon the shaft behind the commutator, intermittent blasts of air are blown exactly at the right moment so as virtually to blow out the spark. The three segments of the commutator are separated

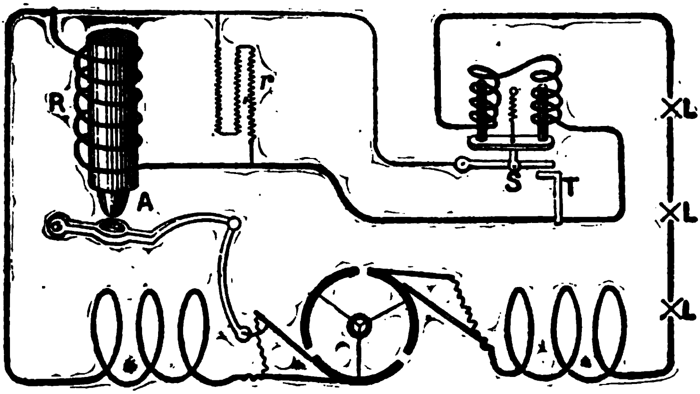


FIG. 815.—CIRCUITS OF THOMSON-HOUSTON SYSTEM.

by gaps; and in front of each of the leading brushes there projects a nozzle which discharges a blast, alternately, three times in each revolution.

Advantages of Open-coil Dynamos.—The two great typical open coil dynamos—those of Brush and of Thomson-Houston—appear to have certain qualities which render them specially applicable as constant-current dynamos for series arc-lighting. A considerable proportion of all the arc-lights in the world are run by one or other of these machines. It would seem that the closed-coil dynamos, whether of the ring or of the drum type, are not so well adapted for furnishing the very high electromotive-forces needed for this work. The commutator, with its many parallel bars insulated with mica (which is the indispensable adjunct of the closed-coil armature), rapidly deteriorates when exposed to the inevitable sparking and wide alterations of lead which are inseparable from the constant-current method of working. For this method of distribution of electric energy, nothing will stand wear and tear so well as the simple air-insulated commutators described in this chapter. As a partial set-off against these advantages may be reckoned the somewhat lower plant efficiency of open-coil machines. The fluctuations in the current in well-designed machines are practically negligible. Mr. Mordey passed the current from a Brush machine through the secondary coil of a transformer, and found that no measurable difference of potential was produced at the terminals of the primary.

Some tests of a closed-coil arc dynamo have been published by Owen and Skinner in the 'Proceedings of the American Inst. Electrical Engineers' for 1893.

A special study of the curves of induction in the armature of a Thomson-Houston arc-light machine has been made[1] by Mr. Milton E. Thompson, who found the total current at full load to fluctuate between five and eight amperes, six times in each revolution, the mean current being 6·8. The fluctuations of electromotive-force in each individual coil were very remarkable; the curves being singularly irregular, falling to near zero twelve times in each revolution.

[1] *Electrical World*, xvii. 392, 1891, and *Electrical Review*, xxviii. p. 773, 1891.

OTHER ARC-LIGHT MACHINES.

Bradley's Dynamo.—Mr. C. S. Bradley has constructed a dynamo with a closed ring armature, in which the difficulty of commuting at high pressure is reduced by having four distinct commutators, the brushes of which are joined in series. A machine of somewhat similar type, designed by M. Hurmuzescu for testing purposes, is described in the next chapter.

Sperry's Dynamo.—An arc-light dynamo with a Gramme armature is that of Sperry, the distinguishing feature of which is the use of internal as well as external pole-pieces. It was illustrated in the previous edition of this book.

Wood's Dynamo. — This is also a modified Gramme machine.[1] To obviate sparking, there is an auxiliary brush placed 5 to 10 sections ahead of the collecting brush; and the voltage is varied by a device which shifts the brushes forward. The width between the auxiliary brush and that behind it is varied, being narrow where commutation has to occur in strong fields, and wide for weak fields, thus securing sparkless reversal in either case. One of the largest arc-lighting stations in the world, that at St. Louis, Missouri, is supplied with 53 of these dynamos, each capable of feeding 60 arc lamps.

Phœnix Arc Dynamo.—Mr. W. B. Esson designed arc-light dynamos[2] for Messrs. Paterson and Cooper, using Gramme ring armatures; and found no difficulty in constructing them from 800 up to 1500 volts. To promote sparkless collection in all positions of the brushes, the field in the gap space must be very constant. Hence in such machines the magnets are made with a less quantity of iron carried to a higher degree of saturation.

Statter's Dynamo.—Another example of a constant-current dynamo, with an automatic regulator to shift the brushes, is afforded by Statter's machine, in which, by a careful shaping of the pole-faces, a disposition of the magnetic field is obtained which permits the machine to run sparklessly.

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[1] See *Electrical World*, xii. April 23, 1887, and xiv. 54 and 260, 1889; also xvii. 4. 1891.

[2] *Journal Inst. Electrical Engineers*, xix. 161, 1890.

Many other makers, Mr. Crompton, Messrs. Mather and Platt, Messrs. Siemens Bros., Messrs. J. H. Holmes & Co., make good arc-light machines, with the general features of closed-coil armatures, commutators having many parts, and magnet-cores well saturated.

F. B. Crocker[1] has pointed out that it is desirable to use carbon brushes with high-voltage closed-coil dynamos, as copper wears off on the mica insulation, causing a thin film of copper which promotes sparking.

He has constructed a 5 horse-power continuous-current dynamo having 108 parts in the commutator, capable of yielding 11,000 volts.

Drooping Characteristics.—A method which, though not in itself securing constancy of current, is much followed in the construction of arc-lighting dynamos, should here be explained. Attention was drawn on p. 205 to the drooping form of the characteristics of certain series-wound machines. It is obvious that if this effect is sufficiently exaggerated, the drooping portion of the characteristic will correspond to the case of an approximately constant current. The drooping characteristic is important (see p. 223) in promoting the steady working of arc lamps in the circuit.

The causes that tend to cause the characteristic of the series dynamo to turn down after reaching a maximum height are: (1) the demagnetizing effect of the armature current when there is a positive lead at the brushes; (2) the saturating of the iron of the armature core and that of the field-magnets; (3) the leakage of magnetic lines from the field-magnet; (4) the peculiar commuting arrangements in certain machines—for example, the open-coil dynamos mentioned previously—which make their effective electromotive-force vary greatly with the position given to the brushes; (5) high internal resistance, and self-induction. As the demagnetizing effect of the armature current is nearly proportional to the current and to the angle of lead, and as the angle of lead is itself nearly proportional to the armature current, it follows that the whole demagnetizing effect is nearly proportional to the square of the armature current. In Fig. 316, let the curve E_1 represent the electromotive-force (at a given speed) when the field-magnets are separately excited, the armature circuit being left open; this includes the effect of (2) and partially (3) above. On the same diagram a curve having ordinates proportional to C_a^2, and of such a magnitude as to represent the demagnetizing action of the armature current, may be plotted. Deducting the ordinates of this curve from those of curve E_1 we get curve E_2, the drooping characteristic. The trouble with all machines of this class is the sparking at the brushes consequent on the variability of the angle of lead.

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[1] Address before Electrical Congress, Chicago, Aug. 24, 1893.

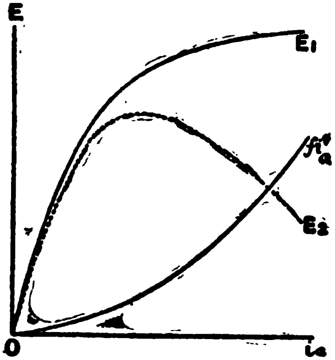

FIG. 316.

The effect of a drooping characteristic can to some extent be obtained by inserting in the external circuit a resistance of from 1 to 2 ohms. And this is preferable to having an internal resistance that would add to the heating of the armature. But such auxiliary resistance should be coiled on an iron core, since self-induction here is of value in steadying the current.

Constant-Current Regulators. — A number of devices applicable to arc-light dynamos are described in Chapter XXIX.

CHAPTER XIX.

MISCELLANEOUS DYNAMOS.

In this chapter are included Dynamos for Electrometallurgy, Homopolar Dynamos, Disk-Dynamos, and other miscellaneous forms.

DYNAMOS FOR ELECTROPLATING AND ELECTROMETALLURGY.

Special forms of continuous-current dynamos are needed for the work of electroplating, electrotyping, and the electrolytic treatment of ores and purification of metals. In general, low electromotive-forces and very large currents are requisite, for the quantity of metal deposited in the bath depends upon the quantity of amperes of current only, and not on the number of volts of electromotive force. And though a few volts are necessary to drive the requisite current through the resistance of the circuit, the number is in every case small. To decompose water electrolytically requires less than two volts. To deposit metal in a bath in which the anode is of the same metal as the deposit requires usually a very small electromotive-force. In general, if too great an electromotive-force is employed, or if the density of current (i. e. the number of amperes per unit of area of kathode surface) is permitted, the metallic deposits will be uneven or pulverulent. All these circumstances point to the construction of dynamos having at most but four or five volts of electromotive-force, but so designed as to have an exceedingly low internal resistance. If, however, as in some processes where equal currents are wanted in a number of tanks, the tanks are placed in series, the voltage needed will be greater in proportion to the number of cells. For example in Castner's process for making caustic soda by electrolyzing common salt solution, each tank needs 2·3 volts, so twenty tanks in series will need 46 volts.

The first application of a dynamo to the purpose of electroplating is due to Mr. J. S. Woolrich, who in 1842 patented this use of a magneto-electric machine. Wilde, however, was the first to construct machines really fitted for the purpose, when he invented the principle of using a large dynamo, the field-magnets of which were separately excited by the currents of a smaller magneto machine. His first machines, which were used for many years by Messrs. Elkington, had small exciters of the old Siemens type (Fig. 23), mounted upon electromagnets of the form shown in Fig. 100, No. 1. Both armatures were of the old shuttle-form, introduced by Siemens, and the larger one required to be kept cool by streams of water. About the year 1867 Wilde introduced a multipolar machine with a redressing commutator. Weston introduced a small machine for nickel-plating which had steel cores to the magnets but with main-circuit coils upon them, and an automatic cut-off to break the current, to prevent the magnetism from reversing by a back-current from the bath. The commutator merely rectified the currents (p. 38) without rendering them continuous. This is a bad feature; the fluctuations of the current ought to be reduced to a minimum by employing a many-part armature with a proper collector. Elmore built large dynamos, for copper refining, with eighteen electromagnets in each crown, yielding a current of 3000 amperes at a potential of seven to eight volts. Such a machine would deposit over 25 lbs. of copper per hour. The field-magnet coils were unfortunately in series with the main circuit. All electroplating dynamos should be shunt-wound or they are liable to reverse their polarity. Gramme in 1873 built special forms of very low resistance with strip-wound armatures having a commutator at each end, and giving 1500 amperes at 8 volts. Siemens and Halske also were early in the field with machines having bar armatures, which they employed at their electrolytic works at Oker.[1] Brush also constructed large machines of low resistance for electroplating purposes. These machines had coarse wire coils connected in series, and a shunt, or so-called " teazer " coil, of finer wire to maintain the magnetism when the main circuit was opened; thus enabling the machine to do either a large or a small amount of work without fear of reversing the current. The voltage of this machine varied only from 3·3 to 4·1 volts, whilst the current varied from 300 amperes to zero.

Other dynamos have been designed for electroplating and electro-metallurgical work by nearly all the important manufacturers.

An Elwell-Parker depositing dynamo[2] gave 1500 amperes at 50 volts at 450 revolutions per minute; a 4-pole shunt-wound drum machine, with 80 stranded conductors, each of 0·2 square inch section, on the drum, and a 40-part commutator. Armature is 20 inches long and 22 inches diameter, with an unusually long commutator. Four sets of brushes, five in each set. Length of active conductor 1600 inches. At peripheral speed of 2500 feet per minute generates 1 volt for each 8 inches of conductor.

A 50 kilowatt dynamo, by Paterson and Cooper,[3] for producing bleaching liquor electrolytically, gives 1200 amperes at 42 volts.

Another 50 kilowatt dynamo, designed by Hopkinson[4] for copper refining, gives 1000 amperes at 50 volts, at 400 revolutions per minute; resistance of armature 0·0016 ohm; commercial efficiency 93 per cent.; total weight 5½ tons.

A plating dynamo by Stafford and Eaves[5] has solid and simple magnetic circuit with one exciting coil and a ring armature with only eighteen sections, giving 150 amperes at 6 volts at 640 revolutions per minute.

In dynamos for such purposes the requirement of large current and very low voltage introduces difficulties into the design, for the voltage cannot be obtained low enough without having either very few convolutions on the armature, or else a weak field-magnet, or else a very slow-speed machine.

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[1] See *Elektrotechnische Zeitschrift*, ii. 54.

[2] *Electrician*, xxi. 183, 1888.

[3] *Ibid.*, p. 181.

[4] *Ibid.*, xvii. 62, 1886.

[5] *Ibid.*, xviii. 506, 1887.

Slow-speed machines are always costly in proportion to their output. Machines with weak magnets give trouble with sparking. Machines with few massive conductors and few parts in commutator give trouble in sparking, and are liable to heat from local eddy-currents. A stranded conductor should be used, or several *independent* windings (see pp. 272 and 406), all put in parallel by brushes of special thickness.

Sayers has proposed an ingenious device to enable currents to be taken from a machine at various voltages. The pole surfaces are subdivided by deep nicks as in Fig. 317, thus providing several neutral points on the commutator at which brushes may be placed without sparking. Thus, for example, whilst the potential between the two main brushes may be 10 volts, an intermediate brush may be employed to divide this into 7½ volts for nickeling and 2½ volts for silver-plating.

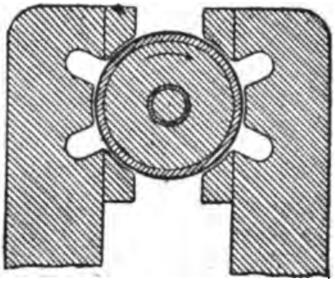

FIG. 317.—SAYERS' DYNAMO FOR ELECTROPLATING.

Messrs. Crompton & Co. have devised a method of dividing the main leads between two pairs of brushes touching adjacent bars of the commutator, and are thereby enabled to construct their plating machines with fewer parts in the armature. The divided leads from the dynamo to the plating tanks cost no more than a single undivided lead would do, but they interpose a comparatively large resistance in the path of the local current from the short-circuited section.

For the special purpose of the aluminium industry several types of machines have been developed. Messrs. Crompton & Co. built a very large 2-pole drum machine,[1] capable of affording 5000 amperes at 60 volts. Mr. C. E. L. Brown[2]

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[1] *Electrician*, xxi. 590, 1888; also *La Lumière Electrique*, xxx. 207, 1888.

[2] *La Lumière Electrique*, xxx. 205, 1888; *Electrician*, xxi. 727, 1888.

designed for the Oerlikon Works some 6-pole machines for 6000 amperes at 20 volts at 180 revolutions per minute. The armatures have each two separate windings with a commutator at each end, and at each commutator 36 brushes, arranged in six sets of six each. The field-magnet is like Fig. 108, but with six poles, and cast in one piece. The armature is 38 inches in diameter and 24 inches long. The windings were at first embedded in holes in the core-disks; but as troubles arose about insulation, the core-disks were turned down and the armature re-wound with external conductors. Although there are as many brush-sets as poles, rendering cross-connection of the windings not absolutely necessary, yet such cross-connections are added to ensure equalization of the currents, equipotential segments of the commutator being internally cross-connected by rings with three projecting lugs. Mr. Brown has also made some 8-pole machines for an output of 14,000 amperes at 30 volts. The 8-pole and 24-pole generators of the Oerliken Company are described on p. 412 above.

Some statistics relating to electro-metallurgy will be found in Appendix B.

DYNAMOS FOR ACCUMULATOR-CHARGING.

In central-station work where batteries of accumulators are used, the usual practice is to employ shunt dynamos capable of giving 25 or 30 per cent. higher electromotive-force than that at which the battery is to discharge; and their circuits are usually arranged so that the mains can be supplied, according to demand, either from the dynamos and accumulators together in parallel at the time of maximum load or from either separately.

Whenever dynamos are wanted for the sole purpose of charging accumulators, it is better to design them specially so that their magnets are not too highly saturated under working conditions. For then, during charging, when the counter electromotive-force of the cells gradually rises, the voltage of the dynamo also rises automatically, instead of remaining nearly constant as it would do if the magnetism were incapable of further rise. The result is that the charging current remains more nearly constant without intervention of an attendant.

EXTRA-HIGH PRESSURE DYNAMOS.

For transmission of power to long distances by continuous currents, and for laboratory purposes, dynamos are occasionally required giving extra-high pressure. Croker [1] has constructed a machine yielding 0·3 of an ampere at 11,000 volts, the commutator consisting of 108 parts. He recommends carbon brushes for such machines, in order to minimize the sparking. Under the direction of M. Hurmuzescu, a continuous current dynamo [2] of exceptionally high voltage has been built for the physical laboratory of La Sorbonne, by La Société Cail, to whose chief, M. Helmer, the details of the design are due. The normal output of the machine is 2 amperes at a pressure of 3000 volts, but it has yielded a pressure of 4000 volts with ease. A longitudinal section of half of the machine is shown in Fig. 318, there being altogether four armatures on the same shaft. Fig. 319 gives two different cross sections. The shape of the field-magnets being sufficiently indicated in the drawings, needs no description. The special advantage of this type of field-magnet is, that a perfectly symmetrical field is obtained without the additional cost of copper that is incident to a double magnetic circuit. There are four armatures of the ring type mounted on the same shaft, each giving a pressure of 750 volts at a speed of 1500 revolutions per minute. The winding consists of 160 sections of 66 turns per section, so there are 10,560 wires on the periphery. Each commutator is 20 cms. in diameter, and consists of 160 segments, there being a maximum of 10 volts between any two segments. The resistance of armature is 128 ohms.

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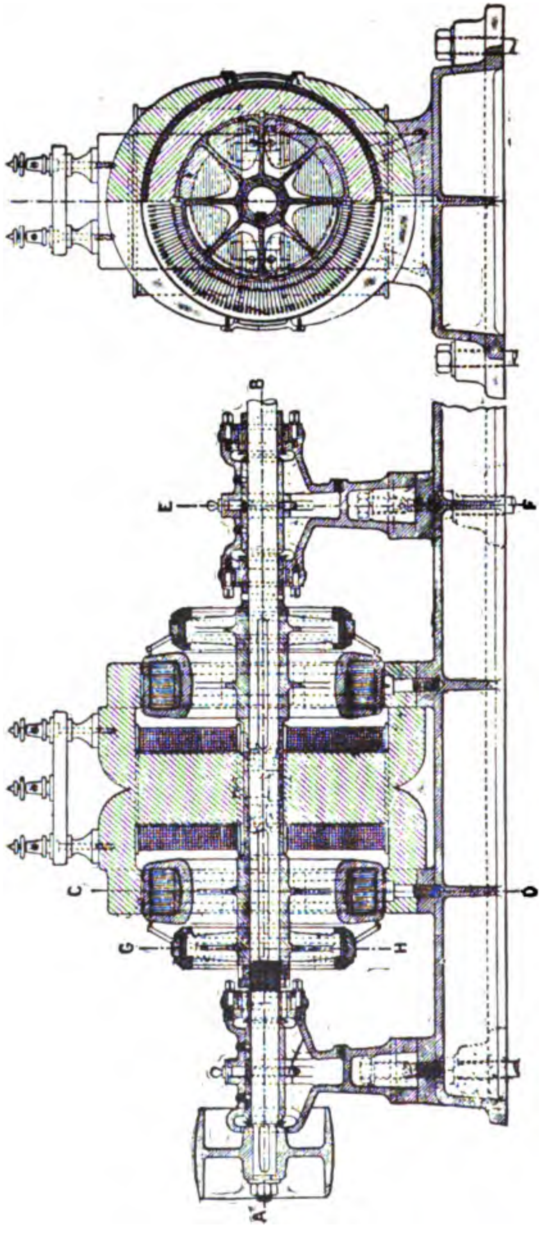
[1] Address before the Electrical Congress, Chicago, August 24, 1893, *Electrical World*, xxii. 201.

[2] *L'Industrie Electrique*, July 10, 1895, p. 290.



FIGS. 318 and 319.—SECTION OF A 3000-VOLT CONTINUOUS-CURRENT DYNAMO.

HOMOPOLAR ("UNIPOLAR") DYNAMOS.

In those cases where the motion is such that the conductor moves continuously past poles of one kind only, the inductive operation is said to be *homopolar;* in cases where it passes from being opposite a N-pole to being opposite a S-pole, the operation is said to be *heteropolar.* Heteropolar operations obviously generate alternate currents, unless a commutator is added. Homopolar operations give rise to a continuous induction of electromotive-force if the field is also continuous, the rotation of the conductor effecting a continuous cutting of the magnetic lines without any reversal in direction; but in such cases, sliding connections are necessary to collect the current. Machines giving currents by continuous homopolar induction were formerly known[1] as "unipolar" machines. If the homopolar operation is arbitrarily rendered discontinuous, as in Mordey's alternator and in some of the "inductor" alternators, by dividing up the pole-face into separate projections, and the conductor is wound alternately backwards and forwards across the field, the result will be an alternating induction.

The earliest machine which has any right to be called a dynamo (Fig. 1, p. 5), namely, the rotating copper disk of Faraday, was, in fact, of the homopolar class. So were his other machines with sliding connections; for example, the copper cylinder rotating over the pole of a magnet (Fig. 3, p. 6). Plucker[2] devised another form, with a horizontally rotating magnet, having sliding contacts at the middle and at either end. In 1862 Mr. S. A. Varley had a homopolar apparatus with an iron magnet rotating in a vertical frame having a mercurial connection at the middle-point. About 1878 Dr. Werner Siemens[3] designed a homopolar machine in which there were two cylinders of copper, both slit longitudinally to obviate eddy-currents, each of which rotated around one pole of a U-shaped electromagnet. A second electromagnet was placed between the rotating cylinders, with protruding pole-pieces of arching form which embraced the cylinders above and below. Each cylinder, therefore, rotated between an internal and an external pole of opposite polarity, and consequently cut the lines of force continuously by sliding upon the internal pole. The currents from this machine are very great, but of only a few volts of electromotive-force. To keep down the resistance, many collecting brushes press on the cylinders at each end. This dynamo was used at Oker for depositing copper. Much attention has been paid in recent years to machines of this type, and the author himself designed one in which two Faraday disks, coupled at their peripheries outside an internal stationary pole-piece, rotate in a symmetrically uniform field. Mr. Willoughby Smith showed that if an iron disk be used instead of a copper disk a much more powerful effect is obtained. Prof. George Forbes has constructed several machines of this class. Originally he began by employing an iron disk which rotated between two checks of opposite polarity, the current being drawn from its periphery. He then doubled the parts. The next stage was to unite the two disks into one common cylinder, rotating within an entirely self-contained iron-clad field-magnet. For this reason the inventor prefers to call this type of dynamo "non-polar." A rubbing contact—for which purpose Prof. Forbes at one time used carbon brushes, and at another a number of springy strips of metal foil—is maintained at the two extremities of the periphery. One of the earlier forms of machine, with a single disk 18 inches in diameter, was stated to give 3117 amperes at a potential of 5·8 volts when running at 1500 revolutions per minute. One of the later machines, in which the armature is a cylinder of iron 9 inches in diameter, 8 inches long, is designed to give a current of 10,000 amperes at 1 volt, at 1000 revolutions per minute. In designing such machines it is convenient to remember that the voltage may be expressed in the formula

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[1] This sounds like a *lucus a non lucendo*, for the magnet has two poles. But the name is derived from the term "unipolar induction," which continental electricians, following Prof. Wilh. Weber, give to the induction of currents by the process of "continuous cutting," which we are now dealing with.

[2] *Pogg. Ann.* lxxxvii. 352, 1852.

[3] *Elektrotechnische Zeitschrift*, ii. 94, 1881.

$$E = v\,l\,\mathsf{B} \div 10^8;$$

where v is the linear velocity of the moving conductor (cms. per sec.), l its length (cms.) at right angles to the direction of motion, and B the flux-density of the field. For example, a cylinder of copper, 20 cms. broad, revolving in a field of 10,000 lines per cm., at a linear speed of 4000 cms. per second will induce 8 volts. The electromotive-force of such machines increases as the square of the linear dimensions. Other types have been designed by E. Ferraris, E. L. Voice, Delafield, Hummel and others, including Atkinson,[1] whose machine is self-exciting. All the important forms prior to 1885 are described and discussed by Uppenborn in the *Centralblatt für Elektrotechnik* of that year, p. 324.

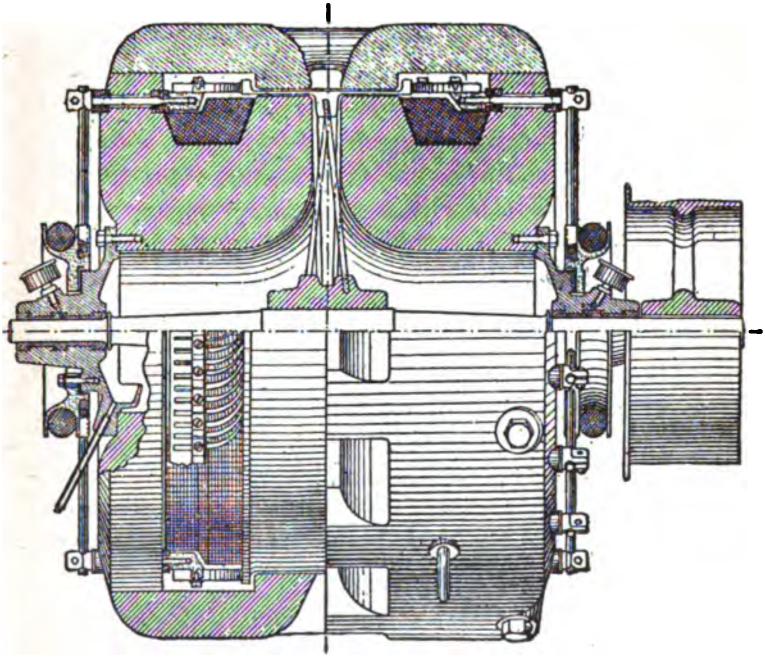

FIG. 320.—BROWN'S HOMOPOLAR DYNAMO.

The theory of the homopolar disk-dynamo has been given by Lord Kelvin,[1] who has shown that such a machine is not self-exciting except above a certain critical speed, dependent on the resistance of the circuit.

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[1] *La Lumière Électrique*, xxxv. 557, 1890.

Two difficulties seem to beset this type of machine, namely, the inherent trouble of peripheral collection of large currents, and the very considerable armature reactions which accompany these large currents, causing great fall in the voltage [2] as the current increases. The latter can only be obviated by the same expedients as hold good in all other types of dynamo, namely, to make the field-magnets relatively powerful and to counterbalance the reactions by compounding or overcompounding the machine by the use of series windings.

Mr. C. E. L. Brown has communicated to the author some results and drawings of a unipolar machine, Fig. 320, built at the Oerlikon Works, with a cylinder of copper rotating between the lips of an iron-clad electromagnet of cast iron. This machine at 1200 revolutions per minute worked at 10 volts and showed hardly any perceptible drop in voltage when 3000 amperes were taken from it. This is the first really practical homopolar machine. Since this was built a closely kindred form has been designed by M. Thury.

Much interest has been shown in recent years in the homopolar type of machine, the theory of which is still to some extent obscure. It will be sufficient to refer to the writings of Tolver Preston,[3] Hering,[4] Arnold,[5] Hoppe,[6] Weber,[7] and Lecher.[8]

DISK-DYNAMOS.

In the dynamos of this class the coils are carried round to different parts of a magnetic field, such that either the intensity differs in different regions, or more generally the lines of force run in opposite directions in different parts of the field. Fig. 17 (p. 29) illustrates this principle; and we shall now consider how it is carried out in practice. In the early machines of Saxton, Clarke and Stöhrer, single pairs of coils were mounted so as to pass in this fashion through parts of the field where the magnetic induction was oppositely directed. Such a machine will, therefore, give alternate currents, unless the commutator be affixed to the rotating axis.

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[1] On a uniform electric current accumulator (*Phil. Mag.*, January 1868; and *Reprint of Papers*, p. 325).

[2] See some figures given by Hummel in vol. ii. p. 19 of Kittler's *Handbuch der Elektrotechnik.*

[3] *Phil. Mag.*, February 1885, March 1885, and February 1891.

[4] *Elec. World*, xxiii. 53, 1894. [5] *Elektrotechnische Zeitschrift*, March 7, 1895.

[6] *Wied. Ann.* xxix, 544, 1886; and xxxii. 288, 1887.

[7] *Elektrotechnische Zeitschrift*, Aug. 15, 1895.

[8] *Wied Ann.* liv. pp. 276-304, 1895.

In 1878 von Hefner Alteneck designed a disk-dynamo in which the number of coils differed by two, or some other number, from those of the field, and with the employment of a multiple-bar commutator with complicated cross-connections. In 1881 Hopkinson and Muirhead showed a disk-dynamo with a wave-winding. In 1875 Professor Pacinotti devised[1] a form of disk-armature, which he described as a "transversal electromagnet fly-wheel." The machine, which was exhibited at Paris in 1881, had for field-magnet two electromagnets placed with their contrary poles juxtaposed, forming, as shown in Fig. 321, a single magnetic circuit with two gaps. Though these two gaps passed a disk-armature, constructed of radical conductors arranged to cut the immense magnetic fields. The electromotive-forces induced in these conductors would on the one side be directed radially inwards, on the other radially outwards. The method devised by Pacinotti for connecting the radial conductors into a single closed coil is shown in fig. 200, p. 279. Another type of disk-armature was invented by Lord Kelvin, consisting of a wheel with spokes like a bicycle wheel, with collecting brushes pressing against opposite ends of a diameter. Bollman[2] devised a

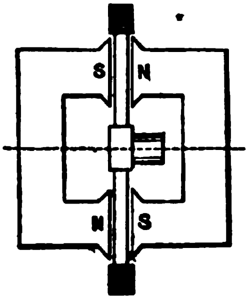

FIG. 321.—FIELD-MAGNETS OF PACINOTTI'S DISK-DYNAMO.

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[1] *Nuovo Cimento* [3] X., September 1881.

[2] For detailed drawings and description, see *Centralblatt für Elektrotechnik.* ix. 7, 1887.

multipolar machine, having a complex armature built up of radial strips of copper connected in zigzag and joined to a cross-connected commutator. More recently machines of this class have been devised by Desroziers,[1] Robin,[2] Jehl and Rupp,[3] and Sayers.[4] The machines of Desroziers have been described on p. 442, and his method of winding on p. 281.

Fritsche's Disk-Dynamos.—These dynamos[5] have a disk with multipolar wave-winding with series grouping for armature. The interesting constructional feature of these machines is the use of wrought-iron bars, instead of copper, as the active conductors in the disk. The commutator is fixed to the outside of the disk, with the brushes trailing against the periphery at two points.

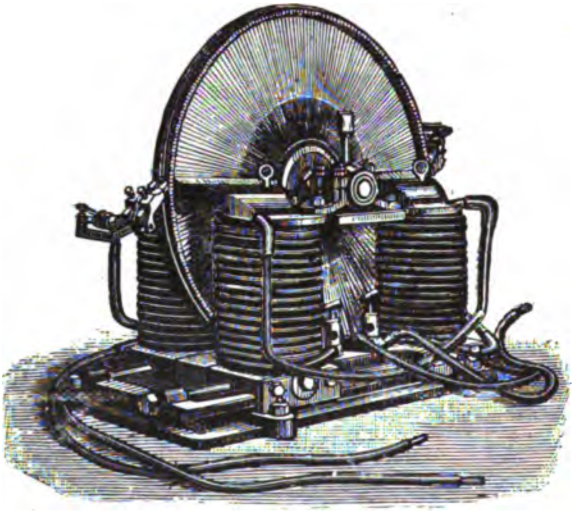

FIG. 322.—POLECHKO'S DISK-DYNAMO.

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[1] See *La Lumière Électrique*, xxiv. 293, 294 and 517, 1887; xxix. 401, 1888; and U. S. Patent No. 459,610.

[2] *Ibid.*, xxiv. 544, 1887.

[3] *Ibid.*, xxiv. 343, 1887. See also detailed illustrations and description in xxv. 368, 1887; and in *Electrician*, xix. 94, 1887.

[4] Specification of Patent, 717 of 1887.

[5] See Fritsche's book, *Die Gleichstrom-Dynamomaschine*, Berlin, 1889; also Specification of British Patent, No. 13,080 of 1887. See also *The Electrician*, xxii. 655, 1888; also *Electrical Review*, xxix. 472, 1891; and *Electrical World*, xii. 205, 1889.

Polechko's Dynamo.—This form[1] realizes Lord Kelvin's suggestion for a wheel-dynamo. The wheel is 1 metre in diameter, with narrow copper spokes to rotate in a narrow gap between the pole-pieces of a pair of electromagnets, arranged to produce a very intense narrow magnetic field along two opposite radii. Fig. 322 shows its form, and the arrangement for collecting the current from the periphery, which is made up of 320 insulated pieces of copper strongly held together by an insulated steel ring at the middle of the rim. It gave, at 1500 revolutions per minute, a current of 2000 amperes at 25 volts; the entire machine weighing 1·1 tons.

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[1] *Journal de la Société Physico-chimique russe*, xxii. 135, 1890.

CHAPTER XX.

CONTINUOUS-CURRENT MOTORS.

In the first chapter, the definition was laid down that dynamo-electric machinery meant machinery for converting mechanical energy into the energy of electric currents, or *vice versâ.* Having dealt with the dynamo in its functions as a generator of electric currents, we now come to its converse function, namely, that of converting the energy of electric currents into the energy of mechanical motion.

An *electric motor*, or, as it was formerly called, an *electromagnetic engine*, is one which does mechanical work at the expense of electric energy. Any kind of dynamo, whether for continuous currents or alternating currents, can be used conversely as a motor, though, as we shall see, some more appropriately than others. Since alternate-current motors differ in their design from those intended to work with continuous currents, they will be considered later on in connection with alternate-current apparatus.

Every one knows that a magnet will attract the opposite pole of another magnet, and will pull it around. We know also that every magnet placed in a magnetic field tends to turn round and set itself along the line of force. It is not, therefore, difficult to understand that very soon after the invention of the electromagnet, which gave us for the first time a magnet whose power was under control, a number of ingenious persons perceived that it would be possible to construct an engine in which an electromagnet, placed in a magnetic field, should be pulled round; and further, that the rotation should be kept up continuously, by cutting off or reversing the current at an appropriate moment. On this very principle was constructed the earliest electric motor of

Ritchie, so well known in many forms as a stock piece of electric apparatus, but little better in reality than a toy. Joule[1] also devised several forms of electric motor.

A still earlier rotating apparatus was Sturgeon's wheel-disk, described in 1823. This instrument, interesting, though a mere toy, as being a forerunner of Faraday's disk dynamo, is a representative of a distinctive class of machines, namely, homopolar machines (p. 475), which have a sliding contact merely, and need no commutator.

A great step in advance was made by Jacobi,[2] who, in 1838, constructed a multipolar motor.

Another class of motors may be named, wherein the moving part oscillates backwards and forwards. Professor Henry constructed, in 1831, a motor with a beam oscillating by the intermittent action of an electromagnet. In Dal Negro's motor of 1833 a steel rod geared to a crank was caused to oscillate between the poles of an electromagnet. A distinct improvement in this type of machine was introduced by Page, who employed hollow coils or bobbins as electromagnets, which by their alternate action, sucked down iron cores into the coils, and caused them to oscillate to and fro.

Page's suggestion was further developed by Bourbouze, who constructed the curious motor depicted in Fig. 323, which looks uncommonly like an old type of steam engine. We have here a beam, crank, fly-wheel, connecting-rod, and even an eccentric valve-gear and a slide-valve. But for cylinders we have four hollow electromagnets; for pistons, we have iron cores that are alternately sucked in and drawn out; and for slide-valve we have a commutator, which, by dragging a pair of platinum-tipped springs over a flat surface made of three pieces of brass separated by two insulating strips of ivory, reverses at every stroke the direction of the currents in the coils of the electromagnets. It is really a very ingenious machine, but, in point of efficiency, far behind all modern electric motors. It does not do to design dynamo-electric machinery on the same lines as steam engines.

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[1] *Annals of Electricity*, ii. 222, 1838; and iv. 203, 1839.

[2] A cut and description of this motor will be found in the former editions of this book.

Yet another now obsolete class of electric motors owed its existence to Froment, who, fixing a series of parallel iron bars upon the periphery of a drum, caused them to be attracted, one after the other, by an electromagnet or electromagnets.

Lastly, of the various historical types of motor we may enumerate a class in which the rotating portion is enclosed in an eccentric frame of iron, so that as it rotates it gradually approaches nearer. Little motors working on this principle of "oblique approach," have long been used for light experimental work.

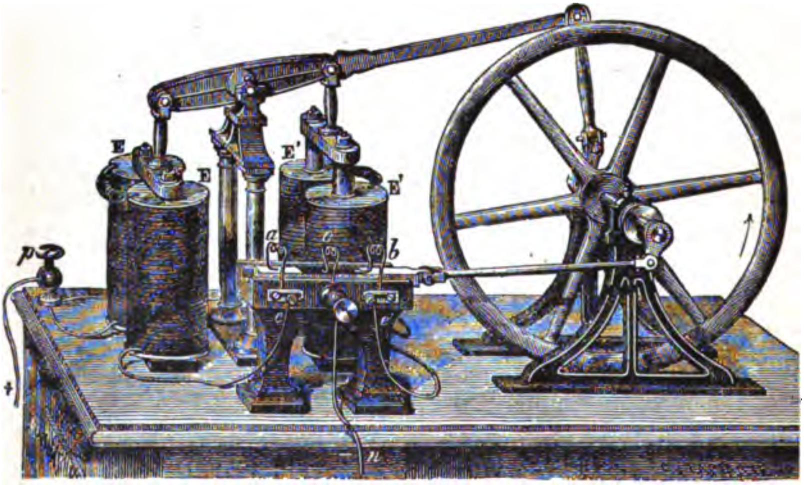

FIG. 323.—BOURBOUZE'S ELECTRIC MOTOR.

It is impossible within the limits of this work to deal with a tithe of all the various stages [1] of discovery and invention.

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[1] An excellent account of the early forms of electric motor, both European and American, is to be found in Martin and Wetzler's *The Electric Motor and its Applications*, third edition, 1891. All readers interested in the subject should also consult the paper on *Electro-magnetism as a Motive Power*, by the late R. Hunt, in *Proc. Inst. Civil Engineers*, xvi., April, 1857, together with the discussion that followed it, in which part was taken by Professor Thomson (now Lord Kelvin), Mr. (now Sir William) Grove, Professor Tyndall, Mr. Cowper, Mr. Smee and Mr. Robert Stephenson. For modern motors they should consult Kapp's *The Electric Transmission of Power*, or Snell's *Electric Motive Power*.

The work of Page, Davidson, Hjorth and others is alluded to in the Historical Notes at the beginning of this book. But the real development came after the commercial introduction of Gramme's dynamos in 1871, as engineers began to understand how two machines could be used—one as generator, the other as motor—to transmit power through a line.

All the earlier attempts to introduce electric motors came to nothing, for two reasons. Firstly, at that time there was no economical method of generating electric currents known; secondly, the great physical law of the conservation of energy was not fully recognized, and its all-important bearings upon the theory of electric machinery could not be foreseen.

While voltaic batteries were the only available sources of electric currents, economical working of electric motors was hopeless; for a voltaic battery wherein electric currents are generated by dissolving zinc in sulphuric acid is a very expensive source of power. To say nothing of the cost of the acid, the zinc—the very fuel of the battery—costs more than twenty times as much as coal, and is a far worse fuel; for whilst an ounce of zinc will evolve heat to an amount equivalent to 113,000 foot-pounds of work,[1] an ounce of coal will furnish the equivalent of 695,000 foot-pounds.

The fact, however, which seemed most discouraging, but which, if it had been rightly interpreted in accordance with the law of conservation of energy, would have been found most encouraging, was the following:—If a galvanometer was placed in the circuit with the electric motor and the battery it was found that when the motor was running the battery was unable to force through the wires so strong a current as that which flowed when the motor was standing still. The faster the motor ran, the weaker did the current become. Now there are only two causes that can stop such a current flowing in a circuit; there must be either an obstructive resistance or else a counter electromotive-force. At first, the common idea was, that when the motor was spinning round, it offered a greater resistance to the passage of the electric current than when it stood still. The genius of Jacobi[1] enabled him, however, to discern that the observed diminution of current was really due to the fact that the motor, by the act of spinning round, began to work as a dynamo on its own account, and tended to set up a current in the circuit in the opposite direction to that which was driving it. The faster it rotated the greater was the counter electromotive-force (or "electromotive-force of reaction") which was developed. In fact the theory of the conservation of energy requires[2] that such a reaction should exist. Joule,[3] by further experiment, found that the counter electric action is proportional to the velocity of rotation and to the magnetism of the magnets.

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[1] A convenient way of regarding the economic question from the point of view of the cost of the voltaic battery is afforded by the following calculation. Supposing the electric motor to convert all the electric energy of the battery without loss into mechanical energy, the amount of zinc used per horse-power in one hour will be almost exactly two pounds divided by the volts of the electromotive-force of the cell employed in the battery.

Two points are vital to the right understanding of the action of electric motors: (1) The propelling drag; (2) the counter electromotive-force. The first is that the real driving-force which propels the revolving armature is the drag which the magnetic field exerts upon the armature wires through which the current is flowing, or, in the case of deeply-toothed armatures, on the protruding teeth: the second is that the revolving armature generates a counter electromotive-force as its moving wires cut the magnetic lines.

The Propelling Drag.—In Chapter V., on the mechanical actions in armatures, the drag, which a magnetic field exerts on a conductor carrying a current, has been explained, and calculations about its magnitude given. In a generator the drag acts in a direction which opposes the rotation, and is, in fact, a counter-force or reaction against the driving force. In a motor the drag is the driving force, and produces the rotation.

The Counter Electromotive-force.—Let it be remembered that wherever in an electric circuit, current flows through some portion of the circuit in which there is an electromotive-force, the current will there either receive or give up energy according to whether the electromotive-force acts *with* the current or *against* it. This will be made clearer by Fig. 324 representing a circuit in which there are a dynamo and a motor. Each is rotating right-handedly, and therefore generates an electromotive-force tending upwards from the lower brush to the higher. In each case the upper brush is the positive one. But in the dynamo, where energy is being supplied to the circuit, the electromotive-force is in the same direction as the current; whilst in the motor where work is being done, and energy is leaving the circuit, the electromotive-force is in a direction which opposes the current. There ought to be no difficulty in understanding that this electric reaction is an essential of motor working.

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[1] *Mémoire sur l'application de l'éléctromagnétisme au mouvement des machines* par M. H. Jacobi (Potsdam, 1835).

[2] For a simple explanation of the necessity of a counter electromotive-force, see the author's *Elementary Lessons in Electricity and Magnetism* (edition of 1895, p. 443).

[3] *Annals of Electricity*, viii. 219, 1842, and *Scientific Papers*, p. 47.

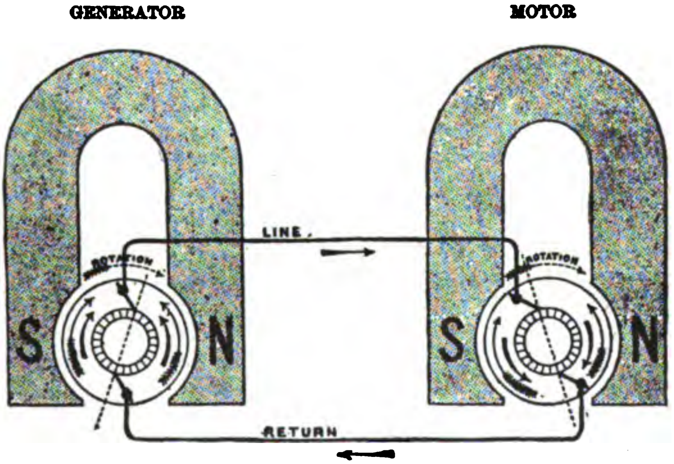

FIG. 324.

Consider the converse case, when we are employing mechanical power to generate currents by rotating a dynamo. Directly we begin to generate currents, that is to say, directly we begin to do electric *work*, it immediately requires much more power to turn the dynamo than is the case when no electric work is being done. In other words, there is an opposing reaction to the mechanical force which we apply in order to do electric work. An opposing reaction to a mechanical force may be termed a "counter-force." When, on the other hand, we apply (by means of a voltaic battery, for example) an electromotive-force to do mechanical work, we find that here again there is an opposing reaction; and an opposing reaction to an electromotive-force is a "counter electromotive-force."

The experiment of showing the existence of this counter electromotive force is a very easy one. All one requires is a little motor with a powerful field-magnet,[1] a few cells of battery of small internal resistance, and an amperemeter. They should be connected up in one circuit, and the deflexion of the amperemeter should be observed when the motor is held fast, and when it rotates with small and large loads. In an experiment, made on a motor with separately-excited magnets, the following figures were obtained:—

Revs. per min. ..	0	50	100	160	180	195
Amperes	20	16·2	12·2	7·8	6·1	5·1

Apparently, if the motor had been helped on to run at 261½ revolutions per minute, the current would have been reduced to zero. The current of 5·1 amperes was needed to drive the armature against its own friction at the speed of 195.

Upon the existence and magnitude of this counter electromotive-force depends, in fact, the degree to which any given motor enables us to utilize electric energy that is supplied to it in the form of an electric current. In discussing dynamos as generators, many considerations were pointed out, the observance of which would tend to improve their efficiency. It is needless to say that such considerations as the avoidance of useless resistances, unnecessary iron masses in cores, and the like, apply equally to motors. The freer a motor is from such defects, the more efficient will it be. But the efficiency of a motor in utilizing the energy of a current depends not only on its efficiency in itself, but on another consideration, namely the relation between the electromotive-force which it itself generates when rotating, and the electromotive-force or electric pressure at which the current is supplied to it. A motor which itself in running generates only a *low* electromotive-force cannot, however well designed, be an *efficient* or economical motor when supplied with currents at a *high* electromotive force.

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[1] One of any ordinary type—a magneto-machine or a series-wound motor will answer.

ELEMENTARY THEORY OF ELECTRIC MOTIVE POWER.

It will be shown, mathematically, that the efficiency with which a perfect motor utilizes the electric energy of the current, depends upon the ratio between the counter electromotive-force developed in the armature of the motor and the electromotive-force of the current which is supplied by the battery. No motor ever succeeded in turning into useful work the whole of the energy that is supplied, for it is impossible to construct machines devoid of resistance; and whenever resistance is offered to a current, part of the energy of the current is wasted in heating the wires that offer the resistance. Let the symbol W stand for the electric power supplied by the mains to an electric motor, and let w stand for that part which the motor takes up as useful power from the circuit.[1] These symbols may stand for the numbers of *watts* respectively supplied and utilized. All that part of the energy of the current which is not utilized by the motor, and transformed into useful work, will be wasted in useless heating of the resistances. The watts lost in heating will therefore be equal to $W - w$.

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[1] The symbol w must be clearly understood to refer to the power taken up by the motor *as measured electrically*. The whole of this power will not appear as useful mechanical effect however, for part will be lost by mechanical friction, and a minute percentage also in the wasteful production of eddy currents in the moving parts of the motor. What proportion of w appears as useful mechanical power depends on the efficiency of the motor *per se*, which we are not here considering. In all that immediately follows we shall suppose such causes of loss not to exist, or the motor will be considered as a perfect motor.

But if we want to work our motor under the conditions of greatest economy, it is clear that we must have as little heat-waste as possible; or, in symbols, w must be as nearly as possible equal to W. It will be shown mathematically that the ratio between the useful energy thus appropriated and the total energy spent, is equal to the ratio between the counter electromotive-force of the motor and the electromotive-force of supply. (As it is not wished here to complicate general considerations by introducing into the expression for the efficiency the energy wasted in heat in the field-magnet coils of the motor, we here assume that the magnetism of the field-magnets is independently excited.) The proof will be given later. Let us denote this whole electromotive-force with which the mains supply the motor (i. e. the volts measured across the terminals of the motor) by the symbol $\mathcal{E}$, and let us call the internal counter electromotive-force E. Then the rule is

$$\frac{w}{W}=\frac{E}{\mathcal{E}}.$$

But we may go one stage further. If the motor be prevented from turning, the current, as calculated by Ohm's law would be

$$C_0=\frac{\mathcal{E}}{R}.$$

If the resistances of the circuit are constant, the current C, observed when the motor is running, will be less than C_0.

$$C=\frac{\mathcal{E}-E}{R},$$

where R is the total resistance of the circuit. Hence

$$\frac{C_0-C}{C_0}=\frac{E}{\mathcal{E}}=\frac{w}{W}.$$

From which it appears that we can calculate the efficiency at which the motor is working, by observing the ratio between the fall in the strength of the current and the original strength.

Though this mathematical law of efficiency had been known for forty years it was for long ignored or misunderstood. Another law, discovered by Jacobi, not a law of efficiency at all, but a law of maximum work in a given time, was given instead. A machine does not generally do its work with the best economy when it performs the greatest work in the least possible time; and the maximum economy or efficiency of an electric motor is not when its output is at a maximum.

Jacobi's law concerning the maximum power of an electric motor supplied with currents from a source of given electromotive-force is the following:—The output of power by a motor is a maximum when the motor is geared to run at such a speed that the current is reduced to half the strength that it would have if the motor was stopped. This, of course, implies that the counter electromotive-force of the motor is equal to half the electromotive-force of supply. Now, under these circumstances, only half the energy furnished by the external source is utilized, the other half being wasted in heating the circuit. If Jacobi's law was indeed the law of efficiency, no motor, however perfect in itself, could convert more than 50 per cent. of the electric energy supplied to it into actual work.

Dr. Siemens, who first made us realize the true physical signification of the mathematical expressions which, until then, had been regarded as mere abstractions, showed, some years ago, that a dynamo can be, in practice, so used as to give out more than 50 per cent. of the energy of the current. In fact, if the motor be arranged so as to do its work at less than the maximum rate, by being geared so as to do much less work per revolution, but yet so as to run at a higher speed, it will be more efficient; that is to say, though it does less work, there will also be still less electric energy expended, and the ratio of the useful work done to the energy expended will be nearer unity than before. Or, instead of gearing it up to run fast, we may gain the same advantage by strengthening its field-magnets.

The true law of efficiency was clearly stated by Lord Kelvin in 1851, and is recognized in a paper by Joule at about the same date.

Jacobi seems very clearly to have understood that his law was a law of maximum working, but not to have understood that it was not a law of true economical efficiency. Jacobi's law is not a law of maximum efficiency, but a law of maximum output; and that is where the error creeps in. It is significant, in suggesting the cause of this remarkable conflict of ideas, that throughout the memoir which he published in 1852, Jacobi speaks of *work* as being the product of force and velocity, not of force and displacement. The same mistake is common enough among continental writers. Now the product of force and velocity is not work, but work divided by time, that is to say, "power," or "rate of working," or "activity." This may account for the widely-spread fallacy. In a paper by Achard in the *Annales des Mines* in January 1879, a clear distinction is drawn between the maximum activity and the efficiency of a motor, and he points out how as the latter increases to a maximum, the former falls to zero. In April, Sir C. W. Siemens and Lord Kelvin gave evidence on electric transmission before a Parliamentary Committee, the latter showing that it was possible to transmit 21,000 H.P. through a copper wire ½-inch in diameter, to 300 miles, provided a potential of 80,000 volts was used. Later in the same year Professors Elihu Thomson and Houston, basing their remarks upon the suggestions of Kelvin and Siemens, proposed to obtain economic results by connecting in series several dynamos at one end of a line, and several motors at the other, so as to work with small currents and high electromotive-forces. The advantage of high voltage in both dynamo and motor at the two ends of the line was never better or more clearly put than by Prof. W. E. Ayrton, in his lecture on "Electric Transmission of Power," before the British Association, in Sheffield in August 1879. These high voltages he proposed to obtain not by increasing the magnetism but by increasing the speed, and by separate excitation of both dynamo and motor. The gain in economy by allowing the motor to run at a high speed with efficiency increasing as its speed increases, was also pointed out by Dr. Werner von Siemens in his address to the Naturforscher meeting in September 1879 (see Werner von Siemens' *Wissenschaftlichen und Technischen Arbeiten*, ii. 374).

Theory of Motors.—If $\mathcal{E}$ be the electromotive-force of the mains supplying the current to the motor when the motor is at rest, and C be the current which flows at any time, the whole electric power W expended in unit time will be expressed in watts, as the product of the whole of the applied volts multiplied by the whole of the amperes, or,

$$\text{(Total watts) } W = \mathcal{E} C = \mathcal{E} \frac{(\mathcal{E} - E)}{R}. \qquad \text{[I.]}$$

Now, when the motor is running, part of this electric power is being spent in doing work, and the remainder is wasting itself in heating the wires of the circuit. The useful part may be similarly written down, as the product of the armature's own volts (the counter electromotive-force) and the amperes, or

$$\text{(Useful watts) } w = E C = E \frac{(\mathcal{E} - E)}{R}. \qquad \text{[II.]}$$

All the power which is not thus utilized is wasted in heating the resistances. So we may write—

Power supplied = power utilized + power wasted in heating or,

$$W = w + \text{watts wasted in heating.}$$

But, by Joule's law, the heat-waste of the current whose strength is C running through resistance R, is expressed by the equation

$$= C^2 R \text{ (watts).}$$

Substituting this value above, we get

$$W = w + C^2 R.$$

Comparing equation [I.] with equation [II.] we get the following:—

$$\frac{w}{W} = \frac{E(\mathcal{E} - E)}{\mathcal{E}(\mathcal{E} - E)};$$

or, finally,

$$\frac{w}{W} = \frac{E}{\mathcal{E}}. \qquad \text{[III.]}$$

This is, in fact, the mathematical law of efficiency, so long misunderstood until Siemens showed its practical significance. We may appropriately call it *the law of Siemens.* Here the ratio $\frac{w}{W}$ is the measure of the efficiency of the motor, and the equation shows that we may make this efficiency as nearly equal to unity as we please, by so adjusting either the magnetism of the field-magnets or the speed of the motor that E is very nearly equal to $\mathcal{E}$.

Now the power utilized is equal to the difference between the total power supplied and the part wasted in heat, or in symbols,

$$w = \mathcal{E} C - C^2 R. \qquad \text{[IV.]}$$

In order to find[1] what value of C will give us the maximum value for w (which is the work done by the motor *in unit time*), we must take the differential coefficient and equate it to zero.

$$\frac{d\,w}{d\,C} = \mathcal{E} - 2\,C R = 0,$$

whence we have

$$C = \tfrac{1}{2}\frac{\mathcal{E}}{R}.$$

But, by Ohm's law, $\mathcal{E} \div R$ is the value of the current when the motor stands still. So we see at once that, to get maximum work per second out of our motor, the motor must run at such

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[1] The argument can be proven, though less simply, without the calculus, as follows : write equation [IV.] in the following form :

$$C^2 R - \mathcal{E} C + w = 0.$$

Solving this as an ordinary quadratic equation, in which C is the unknown quantity, we have

$$C = \frac{\mathcal{E} \pm \sqrt{\mathcal{E}^2 = 4 R w}}{2 R}.$$

To find from this what value of C corresponds to the greatest value of w, it may be remembered that a negative quantity cannot have a square root, and that therefore the greatest value that w can possibly have will occur when

$$4 R w = \mathcal{E}^2,$$

for then the term under the root sign will vanish. When this condition is observed it will follow that

$$C = \frac{\mathcal{E}}{2R},$$

or the current will be reduced to half its original value.

a speed as to bring down the current to half the value which it would have if the motor were at rest. In fact, we here prove the law of Jacobi for the maximum rate of doing work. But here, since

$$C = \frac{\mathcal{E} - E}{R} = \frac{1}{2}\frac{\mathcal{E}}{R},$$

it follows that

$$\mathcal{E} - E = \frac{1}{2}\mathcal{E},$$

or

$$\frac{E}{\mathcal{E}} = \frac{1}{2};$$

whence it follows also that

$$\frac{w}{W} = \frac{1}{2}.$$

That is to say, the efficiency is but 50 per cent. when the motor does its work at the maximum rate.[1]

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[1] It may be worth while to recall a precisely parallel case that occurs in calculating the currents from a voltaic battery. Everyone is familiar with the rule for grouping a battery which consists of a given number of cells, that they will yield a maximum current through a given external resistance when so grouped that the internal resistance of the battery shall, as nearly as possible, equal the external resistance. But this rule, which is true for maximum current (and, therefore, for maximum rate of using up the zinc of one's battery), is not the case of greatest economy. For if external and internal resistance are equal, half the energy of the current will be wasted in the heat of the cells, and half only will be available in the external circuit. If we want to get the greatest economy, we should group our cells so as to have an internal resistance much less than the external. We shall not get so strong a current, it is true; and we shall use up our zincs more slowly; but a far greater proportion of the energy will be expended usefully, and a far less proportion will be wasted in heating the battery cells. The maximum economy will of course be got by making the external resistance infinitely great as compared with the internal resistance. Then all the energy of the current will be utilized in the external circuit, and none wasted in the battery. But it would take an infinitely long time to get through a finite amount of work in this extreme case. The same kind of reasoning is strictly applicable to dynamos used as generators, the resistance of the rotating part of the circuit being the counterpart of the internal resistance of the battery cells. For good economy, the resistance of the armature should be very low as compared with that of the external circuit.

GRAPHIC REPRESENTATION OF LAWS OF MOTORS.

Several graphic constructions have been suggested to convey these facts to the eye; one of these enables us, in one diagram, to exhibit graphically both the law of maximum rate of working, and the law of efficiency.[1]

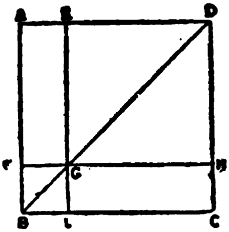

FIG. 325.

Let the vertical line, A B (Fig. 325), represent the electromotive-force $\mathcal{E}$ of the electric supply. On A B construct a square A B C D, of which let the diagonal B D be drawn. Now measure out from the point B, along the line B A, the counter electromotive-force E of the motor. The length of this quantity will increase as the velocity of the motor increases. Let E attain the value B F. Let us inquire what the actual current will be, and what the energy of it; also what the work done by the motor is. First complete the construction as follows: — Through F draw F G H, parallel to B C, and through G draw K G L, parallel to A B. Then the actual electromotive-force at work in the machine producing a current is $\mathcal{E} - E$, which may be represented by any of the lines A F, K G, G H, or L C. Now the electric energy expended per second is $\mathcal{E}$ C; and since $C = \frac{\mathcal{E} - E}{R}$, it may be written as

$$\frac{\mathcal{E}\,(\mathcal{E} - E)}{R};$$

and the electric energy utilized by the motor, measured in *watts*, is

$$\frac{E\,(\mathcal{E} - E)}{R}.$$

R being a constant, the values of the two are proportional to

$$\mathcal{E}\,(\mathcal{E} - E) \text{ and } E\,(\mathcal{E} - E)$$

---

[1] See paper by the author in the *Philosophical Magazine*, Feb. 1883.

Now the area of the rectangle

$$AFHD = \mathcal{E}\,(\mathcal{E} - E),$$

and that of the rectangle

$$GLCH = E\,(\mathcal{E} - E).$$

The ratio of these two areas on the diagram is the efficiency of a perfect motor, under the condition of a given constant electromotive-force in the electric supply.

Turn to fig. 326, in which these areas are shaded. This figure represents a case where the motor is too heavily loaded, and can turn only very slowly, so that the counter electromotive-force E is very small compared with $\mathcal{E}$. Here the area which represents the energy expended, is very large; while that which represents useful work realized in the motor is very small. The efficiency is obviously very low. Two-thirds or more of the energy is being wasted in heat.

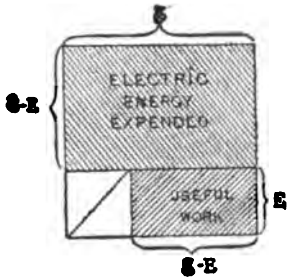

Fig. 326.

So far we have assumed that the efficiency of a motor (working with a given constant external electromotive-force) is to be measured electrically. But no motor actually converts into useful mechanical effect the whole of the electrical energy which it absorbs, since part of the energy is wasted in friction and part in wasteful electro-magnetic reactions between the stationary and moving parts of the motor. What we are expressing thus as useful work is the work actually delivered to the armature to drive it. It is a mere matter of good engineering how small a percentage of this must be discounted for friction in the bearings, eddy-currents, hysteresis and the like. If, however, we might consider the motor to be a *perfect* engine (devoid of friction, not producing wasteful eddy currents, running without sound, giving no sparks at the collecting-brushes, etc.), then we might take the mechanical output as being precisely equal to the actual power delivered electrically to the armature. Such a "perfect" electric engine would, like the ideal "perfect" heat engine of Carnot, be perfectly reversible. In Carnot's heat engine it is supposed that the whole of the heat actually absorbed in the cycle of operations is converted into useful work; and in this case the efficiency is the ratio of the heat absorbed to the total heat expended. As is well known, this efficiency of the perfect heat engine can be expressed as a function of two absolute temperatures, namely those respectively of the heater and of the refrigerator of the engine. Carnot's engine is also ideally reversible; that is to say, capable of reconverting mechanical work into heat.

The mathematical law of efficiency of a perfect electric engine illustrated in the above construction is an equally ideal case; and the efficiency can also be expressed, when the constants of the case are given, as a function of two electromotive-forces.

Law of Maximum Activity (Jacobi). Let us next consider the area G L C H of the diagram (Fig. 325) which represents the work utilized in the motor. The value of this area will vary with the position of the point G, and will be a maximum when G is midway between B and D; for of all rectangles that can be inscribed in the triangle B C D, the square will have maximum area (Fig. 327). But if G is midway between B and D, the rectangle G L C H will be exactly half the area of the rectangle A F H D; or, the useful work is equal to half the energy expended. When this is the case, the counter electromotive-force reduces the current to half the strength it would have if the motor were at rest; which is Jacobi's law of the efficiency of a motor doing work at its greatest possible rate. Also F will be half-way between B and A, which signifies that $E = \frac{1}{2} \mathcal{E}$.

Law of Maximum Efficiency.—Again, consider these two rectangles when the point G moves indefinitely near to D (Fig. 328). We know from common geometry that the rectangle G L C H is equal to the rectangle A F G K. The area (square) K G H D, which is the excess of A F H D over A F G K, represents therefore the electric energy which is wasted in heating the resistances of the motor. That the efficiency should be a maximum the heat-waste must be a minimum. In Fig. 325 this corner square, which stands for the heat-waste, was enormous. In Fig. 327 it was exactly half the energy. In Fig. 328 it is less than one quarter. Clearly we may make the heat-waste as small as we please, if only we will take the point F very near to A. The efficiency will be a maximum when the heat-waste is a minimum. The ratio of the areas G L C H and A F H D, which represents the efficiency, can therefore only become equal to unity when the square K G H D becomes indefinitely small—that is, when the motor runs so fast that its counter electromotive-force E differs from $\mathcal{E}$ by an indefinitely small quantity only.

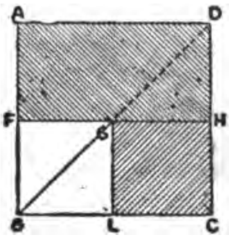

Fig. 327.—Geometric Illustration of Jacobi's Law of Maximum Activity.

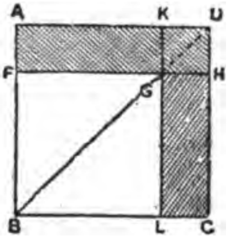

Fig. 328.—Geometric Illustration of the Law of Maximum Efficiency.

It is also clear that if our diagram is to be drawn to represent any given efficiency (for example, an efficiency of 90 per cent.), then the point G must be taken so that area G L C H $= \frac{9}{10}$ area A F H D; or, G must be $\frac{9}{10}$ of the whole distance along from B towards D. This involves that E shall be equal to $\frac{9}{10}$ of $\mathcal{E}$, or that the motor shall run so fast as to reduce the current to $\frac{1}{10}$ of what it would be if the motor were standing still. Thus we verify geometrically, the law of maximum efficiency. If there is leakage in the line, then this law will require modification,[1] for the higher the counter electromotive-force of the motor, the higher will be the potential of the line and the greater the loss by leakage.

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[1] See Kapp's *Electric Transmission of Energy*, 4th edition, p. 185.

It is now evident what we have to do to obtain any desired percentage of efficiency. Suppose current is supplied at 100 volts at the mains: then to utilize 90 per cent. we must employ as motor a dynamo which, when running at its proper speed and output, generates an electromotive-force of 90 volts.

We may now extend the graphic method to a further case.

Suppose that $\mathcal{E}$ is no longer taken as a constant, but that the work to be done by the motor per second is a constant. For this case we may write equation [II.], p. 496, as

$$E\,(\mathcal{E} - E) = w\,R.$$

This equation is graphically represented by the curve P H Q (Fig. 329), in which the values of $\mathcal{E}$ are plotted as abscissæ and those of E as ordinates. From this curve it is at once seen that there will be a certain minimum value of $\mathcal{E}$ which will suffice to give to the motor the prescribed amount of energy per second. The curve is so drawn that it passes through the corner H of all the areas equal to G L C H drawn to fit under the diagonal of the square. Of these areas which represent equal work done by the motor, the one which has minimum value of $\mathcal{E}$ is the square which fits to the apex of the curve and corresponds to the case where $\mathcal{E} = 2$ E. This result, which was first pointed out by Prof. Carhart,[1] is the converse of Jacobi's law, and, like it, involves an efficiency of only 50 per cent. A much higher efficiency is obtained when $\mathcal{E}$ and E are both greater, as indicated by the square drawn through the point *h*.

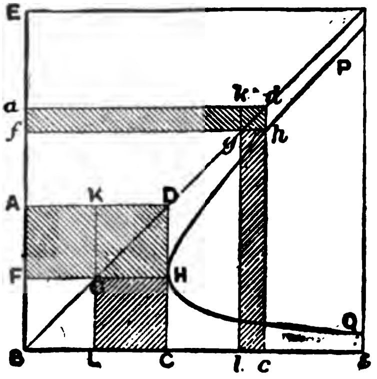

Fig. 329.

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[1] *American Journal of Science*, xxxi. 95, 1886.

SPEED AND TORQUE OF MOTORS.

Certain very important relations subsist between the condition of the electric supply and the speed and turning-moment of a motor.

In Chapter V., on Mechanical Actions and Reactions, it was set forth that the power transmitted along a shaft is the product of two factors, the speed and the torque (or turning-moment). If ω stands for the angular velocity and T for the torque,[1] then

$$\omega\ \mathrm{T} = \text{mechanical work per second, or power.}$$

This may be expressed in watts by use of the proper coefficient.

Now if E is the electromotive-force generated by the armature, and C the current through it, the electric energy per second in the armature is the product—

$$\mathrm{E\ C} = \text{equal electric work per second (in watts}^{2}\text{).}$$

If the whole of these four quantities, ω, T, E and C, are armature quantities, strictly, we may equate the electrical and mechanical expressions together; and the equation will be true for either a motor or a generator In the generator, E and C are in the same direction and T opposes ω; or there is a counter-torque. In the motor, T and ω are in the same direction, but E opposes C; or there is a counter electromotive-force.

---

[1] If n be the number of revolutions per *second*, then $2\,\pi\,n = \omega$. Also if F be the transmitted pull on the belt (or rather the difference between the pull in that part of the belt which is approaching the driving pulley and the pull in that part which is receding from the driving pulley) in pounds weight, and r be the radius of the pulley, F r = the turning-moment or torque = T, then $\omega\,\mathrm{T} = 2\,\pi\,n\,r\,\mathrm{F}$ = the number of foot-pounds per second transmitted by the belt. This may also be proved as follows: Horse-power is product of the force into the velocity. The circumference of the pulley is $2\,\pi\,r$, and it turns n times per second, therefore the circumferential velocity is $2\,\pi\,r\,n$, and this, multiplied by F, gives the work per second. If F is expressed in grammes weight, and r in centimetres, then $2\,\pi\,r\,n\,\mathrm{F}$ will give the power in gramme-centimetres, and must be divided by $7{\cdot}6 \times 10^{6}$ to bring it to horse-power, and must be multiplied by 981×10^{-7} to bring it to watts. If ω is in radians per second and T in dyne-centimetres, then the product will be ergs per second, and can be brought to watts by dividing by 10^{7}.

[2] Since 1 volt = 10^{8} C.G.S. units of electromotive-force, and 1 ampere = 10^{-1} C.G.S. units of current, 1 watt (or volt-ampere) will be = 10^{7} C.G.S. units of work per second = 10^{7} ergs per second = $10^{7} \div 981$ gramme-centimetres per second.

In treating of the dynamo as a generator, it was assumed that the mechanical power could be supplied under one of the two standard conditions, on the one hand of *constant speed* (and torque varying with the electrical output), or else on the other of *constant torque* (and speed varying with the output). One of these two mechanical conditions being prescribed, algebraic expressions had then to be found for the two corresponding factors of the electric output, namely, the *electromotive-force* and the current, under varying conditions of resistance in the circuit. Also we investigated these conditions which would result in making one or the other factor of the electric output constant. It was found convenient to study the relation between the two factors of output by the aid of the curves known as *characteristics*.

Similarly, in treating the dynamo as a motor, it will be assumed that such arrangements of electric supply can be made that the electric power can be furnished under one of the two standard conditions, on the one hand of *constant potential* (and current varying with the mechanical output of the motor), or on the other of *constant current* (and potential varying with the mechanical output). One of these two conditions being prescribed, we shall then have to find algebraic expressions for the two corresponding factors of the mechanical output, namely, the *speed* and the *torque*, under varying conditions of load on the shaft. Also, we shall investigate what are the conditions which will result in making one or other factor of the mechanical output constant: in other words, we shall ascertain what are the conditions of self-regulation to make the motor run at constant speed or with constant torque. Lastly, it will be found convenient to study the relation between speed and torque by the aid of curves, which, by analogy we may call *mechanical characteristics*.

General Expressions for Torque and Speed.

The work imparted per second to the shaft of the motor may be expressed either in electrical or mechanical measure. In the former case it is the product of the motor's electromotive-force (i. e. the counter electromotive-force opposing the electromotive-force of supply) into the current flowing in the armature; in the latter case it is the product of angular speed into torque. So we may write

$$w = \mathrm{E}\,\mathrm{C}_a = \omega\,\mathrm{T} = 2\,\pi\,n\,\mathrm{T};$$

and (average) $\mathrm{E} = n\,\mathrm{Z}\,\mathsf{N}$ exactly as in a dynamo that is being used as a generator (see p. 173). Hence

$$2\,\pi\,n\,\mathrm{T} = n\,\mathrm{Z}\,\mathsf{N}\,\mathrm{C}_a,$$
$$2\,\pi\,\mathrm{T} = \mathrm{Z}\,\mathsf{N}\,\mathrm{C}_a;$$

and finally the average value of the torque will be

$$\mathrm{T} = \mathrm{C}_a \frac{\mathrm{Z}\,\mathsf{N}}{2\,\pi}. \quad . \quad . \quad . \quad . \quad . \quad . \qquad [a].$$

From this it appears that if N is constant, the torque is simply proportional to the current in the armature.

To develop this expression further, we must remember that C_a can be calculated in terms of the electromotive-force of supply $\mathcal{E}$, as measured at the terminals of the machine, and the internal resistance of the circuit through the armature part, which we call r; and then

$$\mathrm{C}_a = \frac{\mathcal{E} - \mathrm{E}}{r};$$

whence it follows that

$$\mathrm{T} = \frac{\mathrm{Z}\,\mathsf{N}}{2\,\pi} \cdot \frac{\mathcal{E} - n\,\mathrm{Z}\,\mathsf{N}}{r} \quad . \quad . \quad . \quad . \quad . \qquad [\beta.]$$

From this it follows that when the speed becomes so great that $n\,\mathrm{Z}\,\mathsf{N} = \mathcal{E}$, there will be no torque. In fact, when there is no resisting force on the shaft the motor runs empty at its highest speed, namely, such as will make the counter electromotive-force as nearly as possible equal to the electromotive-force of supply. The maximum value of T, supposing N constant, is obviously when $n = 0$.

An expression for the speed can be obtained from the preceding:

$$2\pi T r = Z \mathsf{N} \mathcal{E} - n Z^2 \mathsf{N}^2;$$

$$n = \frac{\mathcal{E}}{Z\mathsf{N}} - \frac{2\pi T r}{Z^2 \mathsf{N}^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad [\gamma].$$

In equation [α] T will be expressed in dyne-centimetres if C_a is in absolute C.G.S. units of current; if C_a is given in amperes, then the value must be divided by 10 if T is to be obtained in dyne-centimetres, or by 9810 if it is to be obtained in gramme-centimetres, or by $13{\cdot}56 \times 10^7$ if the torque is to be expressed in pound-feet (*i.e.* so many pounds weight acting at a radius of one foot).

In equation [γ], in order that n may be expressed in revolutions per second, the value of $\mathcal{E}$, if given in volts, must be multiplied by 10^8; that of r, if in ohms, by 10^9. whilst T must be reduced to dyne-centimetres. If T is given in pound-feet, its value must be multiplied by $1{\cdot}356 \times 10^7$.

Examples:—(1) In one of Brown's 4-pole machines used as motor, $Z = 368$; $C_a = 275$; giving 250 H.P. at 500 revs. per minute. Calculate the number of magnetic lines that must go through the armature. (2) A 2-pole motor is required to supply 4 H.P. in an arc-light circuit in which the current is kept at 10 amperes: How many volts must it generate? Assume $\mathsf{N} = 2{,}000{,}000$, and that the speed is 15 revs. per second, how many armature conductors must it have?

The three equations [α], [β] and [γ] are true, not only for motors, but for generators, the $\mathcal{E}$ of the formulæ being in the latter case replaced by e. This will give negative values for T, the significance of the sign being that the torque due to the action of the magnetic field on the conductors carrying the armature current is such as to oppose the driving.

If r is very small, and N relatively very large, the second term may be neglected, and the speed will then depend on the first term only. It will be the smaller as N is greater: this being the simple converse of the corresponding fact that the more powerful the magnetic field the less need be the speed of the dynamo to give the desired output. We may also notice that if N is constant, the speed is proportional to $\mathcal{E}$: it will be constant if the condition of supply is that of constant potential, but will be variable if $\mathcal{E}$ varies. If the motor is to do its work at a slow speed, Z should be great as well as N.

We must next inquire how n and T are affected by the fact that the value of N depends upon the construction and winding of the field-magnet of the motor, and by the conditions of supply. We shall consider the following kinds of machine:—

A. *Magneto Motor* and *Separately-excited Motor.*
B. *Series-wound Motor.*
C. *Shunt-wound Motor.*
D. *Compound-wound Motor.*

In each instance we shall have to take into account the conditions of supply, according as $\mathcal{E}$ or C is constant.

MAGNETO MOTOR AND SEPARATELY-EXCITED MOTOR.

It is here assumed that N is constant, in other words, that the perturbing reactions of the armature may be neglected. Under these circumstances the general formulæ already found require small modification. The only internal resistance is that of the armature r_a.

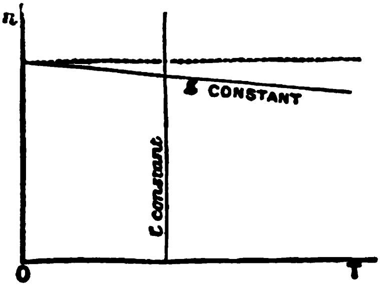

FIG. 330.
MECHANICAL CHARACTERISTICS OF MAGNETO MOTOR.

Case (i.): $\mathcal{E}$ *constant.*

In this case formula [γ] gives the desired relation, from which the *mechanical characteristic* may be plotted out, as in Fig. 330. It is a straight line cutting the axis of n at a point representing to scale that speed at which $n \, Z \, \mathsf{N} = \mathcal{E}$; and it slopes downwards at an angle such that the tangent of the slope is equal to

$2\pi r_a \div Z^2 N^2$, or is proportional to the internal resistance. In the case of the separately excited motor, increase in the exciting current, strengthening the field, will obviously make the sloping line more nearly horizontal, as well as lowering the speed as a whole.

If we attempt to take into account the reactions of the armature, we must remember that the effect of the armature current is to demagnetize, if there is a backward lead, and to magnetize if there is a forward lead. A backward lead, then would tend to make the sloping line, at constant $\mathcal{E}$, rise and become more level as the torque increased, because it would weaken the magnet, and so let the speed increase; whilst a forward lead would tend to make it slope still more.

Case (ii): C *constant.*

In this case, as reference to formula [*a*] shows, the torque is constant, being independent of speed and of internal resistance. The mechanical characteristic of the machine under these conditions is a vertical straight line.

SERIES MOTOR.

The fundamental equations are as before, with the addition of the following:—

$$r = r_a + r_m;$$

but now we may with advantage introduce the approximate formula for the law of the electromagnet (derived from Frölich's) given in Chapter VI., and write, as on p. 143, where C′ is the diacritical current and $h = S\,C'$,

$$N = \overline{N}\,\frac{C}{C + C'}.$$

Putting this value of N into the expression [*a*], on p. 503, for the torque, and writing for brevity $\frac{Z\overline{N}}{2\pi} = Y$, we have

$$T = Y\,\frac{C^2}{C + C'}.$$

This relation between torque and current is given graphically in Fig. 331. For values of C that are small as compared with C′, T varies nearly as C^2; whilst for large values of C, as magnetic saturation advances, T is nearly proportional to C. The equation may also be written in the quadratic form—

$$C^2 - \frac{T}{Y} C - \frac{T}{Y} C' = 0,$$

the solution of which is

$$C = \frac{T}{2Y} \left\{ 1 \pm \sqrt{1 + \frac{4Y}{T} C'} \right\}.$$

It is permissible for large values of T to neglect the second term under the root sign, since the magnetization grows nearly constant.

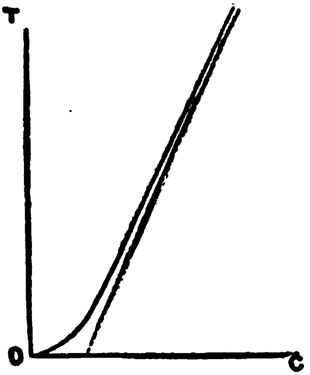

FIG. 331.

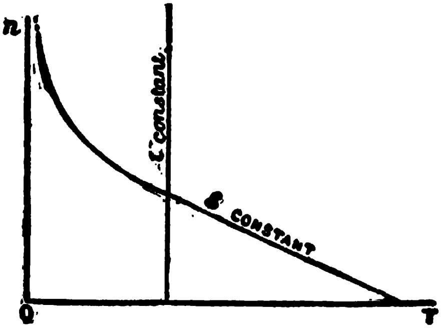

FIG. 332.
MECHANICAL CHARACTERISTICS OF SERIES MOTOR.

As an example plot the following figures taken from a test of a 30 H.P. street-car motor, where the torque is given in pound-feet, the current in amperes, and the speed in revolutions per minute :

Current	3·5	10	20	30	40	50	70	90	94
Torque	0	29	95	183	281	385	610	863	912
Speed :	479	236	145	118	99	85	61	39	35

Now from [a] and [γ] above we may eliminate S N, giving

$$n = \frac{\mathcal{E}\,C}{2\,\pi\,T} - \frac{r\,C^2}{2\,\pi\,T};$$

whence,

$$n = \frac{\mathcal{E}\,C}{2\,\pi\,T} - \frac{r\,(C + C')}{2\,\pi\,Y};$$

$$n = \frac{\mathcal{E} - r\,C'}{2\,\pi\,Y} - \frac{r\,T}{2\,\pi\,Y^2}.$$

Case (i.): $\mathcal{E}$ *constant.*

If $\mathcal{E}$ is constant, then, as the last equation shows, for large values of T the values of n are equal to a certain constant less a quantity proportional to T; or the mechanical characteristic at this point (when the magnets are well saturated) is, for all large values of T, approximately a straight line as shown in Fig. 332.

Case (ii.): C *constant.*

Here, clearly, saving for armature reactions, the magnetization will be constant; hence the torque will also be constant, as in Fig. 330. With a load exceeding a certain amount, the motor will not start; with a lesser load it will race until friction and eddy-currents make up the difference.

The properties of series-wound motors are so important that we may pause to consider them a little more fully. We know that if the current running through a series dynamo be constant, so that its magnetism is constant, the electromotive-force it develops is almost exactly proportional to its speed. It therefore follows that if E is proportional to ω, T will be proportional to C. This is abundantly verified in the case of series motors by experiments. When a Siemens series dynamo was arranged to lift a load of 56 lbs. on a hoist, it lifted this load at the rate of 212 feet per minute, developing a counter electromotive-force of 108·81 volts. The applied electromotive-force was 111 volts, and the resistance of the circuit was 0·3 ohm. The effective electromotive-force was therefore 2·19 volts and the current 7·3 amperes. When the resistance of the circuit was increased to 2·2 ohms, the speed fell to 169 feet per minute, the counter electromotive-force to 94·94; the effective electromotive-force, $\mathcal{E} - E$, was therefore 16·06 volts, and the current 7·3 amperes as before. When 4·8 ohms were inserted, the speed fell to 141 feet per minute, and E to 76 volts; $\mathcal{E} - E$ was 35 volts, and the current 7·3 amperes as before. *With the same load, the same current,* whatever the speed.

The fact that the torque of a series motor depends only on the current is of advantage in the application of motors to propulsion of vehicles (such as tram-cars) which at starting require for a few seconds a power greatly in excess of that needed when running.[1]

In the series motor, when supplied at constant potential, E is not proportional to the speed, because the field-magnetism is not constant, but falls off as E increases, being (if unsaturated) nearly proportional to $\mathcal{E} - E$. It therefore will not run at a constant speed. Neither will it run at a constant speed if supplied with a constant current.

Use of two Series Machines in Transmission.—It is known that if two similarly-constructed series-wound machines are used — one as generator, the other as motor — the arrangement is almost perfectly self-regulating, the speed of the motor at the receiving end being almost constant if that of the dynamo at the transmitting end is constant. Every addition to the load put upon the motor, tending to check the speed, causes an increase of current to flow, and so throws proportionate additional work upon the generator, which in turn takes more power from the steam engine to keep up its speed. As we have shown above, the torque of the motor T_2 will depend, in the given machine, on the current alone, and on the current will depend the torque at the dynamo T_1. Mr. Kapp has further shown[2] how, if there is a resistance in the line, the arrangement may still be made self-regulating by choosing as generator and motor two machines so wound that comparing their characteristics for the prescribed speeds, the difference in their electromotive-forces corresponding to a given value of current shall be equal to the electromotive-force requisite to drive that particular current through the resistance of the whole circuit. See Chapter XXVIII., on Transmission of Power.

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[1] See remarks by E. Hopkinson, *Proc. Inst. Civil Engineers*, xci. pt. i. 6, 1887.

[2] See Kapp's *Electrical Transmission of Energy*, 4th edition, p. 199.

The late Sir C. W. Siemens[1] drew attention in 1880 to the singular properties of the combination of a generating dynamo and an electric motor, instancing a locomotive motor which, when descending an incline, quickens its speed and actually becomes a generator of currents, paying back the spare power into store. He also remarked how two trains driven by motors running on the same pair of electric rails, tend to regulate one another, the one on a descending portion of the road transmitting power to the other, as though "connected by means of an invisible rope."

SHUNT MOTOR.

The fundamental conditions are as follows:—

$$T = C_a \frac{Z\,N}{2\pi};$$

$$C_a = C - C_s;$$

and, adopting the appropriate form for the law of magnetization,

$$N = \overline{N}\frac{\mathcal{E}}{\mathcal{E} + \mathcal{E}'};$$

$$E = \mathcal{E}\left(1 + \frac{r_a}{r_s}\right) - r_a C.$$

From the first three of these we get

$$T = \frac{Z}{2\pi}\left(C - \frac{\mathcal{E}}{r_s}\right)\overline{N}\frac{\mathcal{E}}{\mathcal{E} + \mathcal{E}'};$$

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[1] *Journal Soc. Telgr. Engineers*, ix. 301, 1880.

and, transposing and writing Y for $Z\,\overline{N} \div 2\pi$,

$$C = \frac{T}{Y} \cdot \frac{\mathcal{E} + \mathcal{E}'}{\mathcal{E}} + \frac{\mathcal{E}}{r_s};$$

and from the last of the four

$$n = \frac{1}{Z\,N} \left\{ \mathcal{E}\left(1 + \frac{r_a}{r_s}\right) - r_a C \right\}.$$

Inserting the value of C, we have

$$n = \frac{\mathcal{E} + \mathcal{E}'}{2\pi Y} \left\{ 1 + \cancel{\frac{r_a}{r_s}} - \frac{r_a T}{Y} \cdot \frac{\mathcal{E} + \mathcal{E}'}{\mathcal{E}^2} \right\}.$$

Case (i): $\mathcal{E}$ *constant.*

The last equation shows that a shunt-motor, supplied at constant potential, will have a speed that would be constant and independent of the torque if it were not for internal resistance; and further, that the consequent falling off as the torque increases will be the less as the field-magnetism is the more powerful.

As an example, a Victoria shunt motor tested by Mr. Mordey, in which the load was varied from $91{\cdot}8 \times 10^7$ to $1357{\cdot}2 \times 10^7$ dyne-centimetres, only decreased its speed from 16·25 to 15·75 revolutions per second.

It is instructive to contrast the self-regulating power of a shunt dynamo with the self-governing power of a shunt motor. The former, when driven at a constant speed, generates electric power at a nearly constant potential; the latter, when supplied from the mains at a constant potential, would furnish mechanical power at a nearly constant speed; and in both cases the departure from absolute constancy is proportional to the internal resistance of the armature coils, and to the output electrical or mechanical, of the machine for the time being.

So far we have supposed the armature to exert no magnetic reaction. Now, as we shall see, to obtain sparkless running there must be a backward lead, and in motors a backward lead tends to demagnetize. But demagnetizing tends, as we have seen, to increase the speed; hence in the case of constant pressure supply, when there is a great load, the very reaction of the great current will tend to prevent the speed from falling, making the shunt motor very nearly self-regulating. These reactions must now be considered in detail.

Case (ii.): C *constant.*

The determination of this case is more complicated, though the general considerations are simple enough. If the motor is standing still when the current is turned on, nearly all the current will go through the armature, next to none through the shunt; hence there will be little magnetism, and therefore almost no torque. Such a machine will not start itself with any load on; but if it be once started, its counter electromotive-force will cause the current in the armature to decrease, whilst that round the shunt increases. The torque will therefore then increase with the speed, but not indefinitely, for as the magnetism advances in its degree of saturation, the increase of N will no longer compensate for the decrease of C_a; and from that point onwards the torque will decrease if the speed is allowed to increase. And, hypothetically, the speed should increase until the motor's own electromotive-force exactly equals the difference of potentials due to the whole of the constant current flowing through the resistance of the shunt, under which circumstances there will be no current through the armature and zero torque. Fig. 333, which, like the preceding, is taken from Dr. Frölich's work, gives the mechanical characteristics for the two cases.

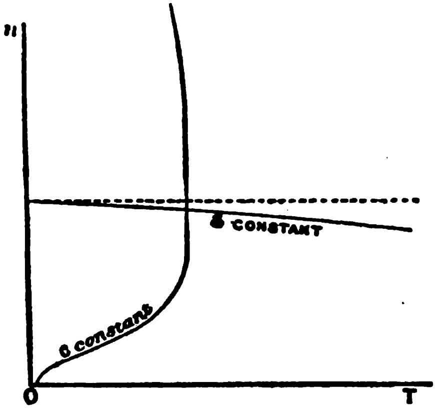

FIG. 333.—MECHANICAL CHARACTERISTICS OF SHUNT MOTORS.

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REACTION BETWEEN ARMATURE AND FIELD-MAGNETS IN A MOTOR.

On pp. 70 to 80 and pp. 380 to 395, the reactions between the armature and field-magnets of a dynamo were considered in detail, but attention was confined solely to that which occurs when the dynamo is used as a generator. In that case we noted that the current in the armature tended to cross-magnetize the armature core and to distort the field in the sense of the rotation; while the forward lead of the brushes, needful for sparkless commutation of the current, tended to exercise a demagnetizing effect. The same thing is true of a motor; but with a difference. A current supplied from an external source magnetizes the armature and makes it into a powerful magnet, whose poles would lie, as in the bipolar dynamo, nearly at right angles to the line joining the pole-pieces, were it not for the fact that in this case also a lead has to be given to the brushes. Suppose, as in most of the drawings in this book, that the S-pole of the field-magnets is on the left, and the N-pole on the right. Also that the current so traverses the armature that it causes the highest point to be a S-pole and the lowest point a N-pole. This means that if the armature is wound right-handedly the current must come in through the top brush and leave by the bottom one, the top brush being connected to the + main. Compare with p. 60. Clearly, in this case, the armature will rotate right-handedly, because the S-pole at the top will be repelled from the S-pole on the left and attracted toward the N-pole on the right. It will therefore run right-handedly (in a right-hand field) when the current flows downwards from top to bottom, exactly as the armature of a generator must run in order to send a current upwards. In each case the direction of the induced electromotive-force is the same—upwards—*with* the current in the generator, *against* the current in the motor.

It follows that in a motor a *forward* lead would convert the cross magnetizing-force into one that tends to increase that of the field-magnet, whilst a *backward* lead tends to demagnetize. Further, since with a forward lead the armature polarity strengthens that of the field-magnet, it is possible (apart from the question of sparking) for a motor to be worked without any other means being taken to magnetize the field-magnets (see p. 395): the armature will induce a pole in the field-magnet and then attract itself round towards this induced pole. This principle has been used for many years in small motors.

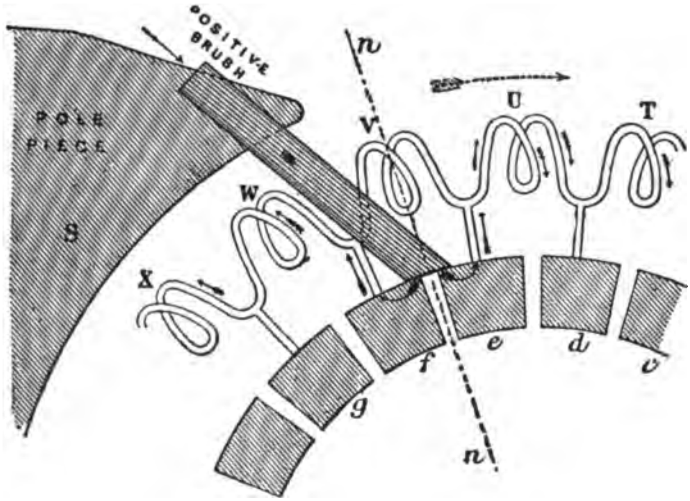

FIG. 334.—THE ACT OF COMMUTATION OF A SECTION OF THE ARMATURE OF A MOTOR.

The cross-magnetizing force will also have the effect of weakening the field under the two leading pole-tips, and of strengthening them under the two trailing pole-tips. This is the opposite effect to that in a dynamo. In the motor (without lead even) the cross-magnetizing reaction tends to shift round the field in a sense *opposite* to that of the rotation. We shall now see what are the conditions for minimum sparking. Consider (Fig. 334) a coil W ascending on the left. The current in it is descending from the top brush, whilst it is itself the seat of an electromotive-force that tends to stop or reverse its current. Now we know that the condition of non-sparking requires that at the moment whilst the coil passes under the brush, and is short-circuited, it should be passing through a field that is not only sufficiently strong, but one that tends to reverse the direction of its current. It is already in such a field; hence the act of commutation must take place *before* it passes out of this magnetic field. It must be commuted before it arrives at the highest point. In other words, a backward displacement must be given to the brushes if there is to be no sparking. The neutral line *n n'* will therefore rake *backwards* in a motor into the fringe of the magnetic field. But since (in every case) both eddy-currents and hysteresis tend to shift the magnetic field slightly in the direction of the rotation—increasing the lead in a generator, diminishing it in a motor—it follows that the negative (or backward) lead in a motor may be slightly less than the positive (or forward) lead in a generator, for equal flow of current and equal excitation.[1] The advantage in point of weight of a motor in which the armature should help to excite the field-magnets, thereby reducing the weight of the latter, led Professors Ayrton and Perry,[2] in 1883, to advocate designs with weak field-magnets and powerful armatures acting with a forward lead. But from the foregoing considerations it follows that if a forward lead is given to the brushes of a motor in order to get a more powerful rotation, the motor will spark at the brushes, unless some special device, such as that used by Sayers, for the prevention of sparking, is employed. Minimum of sparking may be reconciled with high efficiency by so designing and constructing motors that the armature shall not perturb the magnetic field due to the field-magnets. This can be accomplished by following out the very same principles of design and construction which were found to be correct guides in the case of dynamos used as generators (p. 386). Mr. Sayers, whose method of winding armatures with auxiliary commuting coils was considered on p. 395, has applied the same method[1] to the armatures of motors. With this device the current flows through the armature sparklessly even though a considerable forward lead is given to the brushes; and in this way the armature is able to help the magnetization of the field-magnets. For description of a motor on this plan, see p. 540.

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[1] This appears to be the explanation of the differences—otherwise unimportant—observed by Snell; *Journal Inst. Electr. Engineers*. xix. 194, 1890.

[2] *Journal Soc. Telegr. Engineers*, xii. May 1883.

Mr. Mordey,[2] who has carefully tracked out the analogies between dynamos and motors, has observed that in several respects it is even more important that the rules laid down for the good design of generators should be observed for motors. Eddy-currents must be even more carefully eliminated. Also the greatest attention must be paid to proper mechanical arrangements for transmitting to the shaft the forces exerted by the field-magnet upon the armatures.

Contrast the conditions which are bound up in the disposition of the magnetic fields of the generator and the motor respectively. In one the armature is mechanically driven round while the magnetic forces in the field tend to pull it back. In the other, the magnetic forces of the field tend to drag it round, and it is thereby enabled to do mechanical work. In one case there is an opposing mechanical reaction tending to stop the steam engine. In the other there is set up an opposing electrical reaction (the induced counter electromotive-force) tending to stop the current.[3] In both cases the rotation is supposed to be taking place in the same sense—right-handedly. In both the effect is to displace the lines of force of the field, but in the generator the mechanical rotation acts as if it dragged the magnetism round, whilst in the motor the reciprocal magnetic reactions act as if they tried to drag round the armature, producing mechanical rotation. In the usual type of generator we found sparkless reversal to require a positive lead. In the motor, on the contrary, sparkless reversal necessitates a negative lead. If a motor is set with no lead, and if the field-magnets are very weak or are not excited at all, it will run in either direction according as it may be started. If in a motor with well-excited field-magnet the current be reversed in the *armature part* of the circuit only, the motor will usually reverse its rotation, but will usually require the lead to be reversed to run as sparklessly as before. If, instead of reversing the current in the armature, the magnetism of the field-magnet be reversed, a similar result will follow. If both are reversed at the same time, the motor will go on rotating as if nothing had happened.

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[1] *Inst. Electr. Engineers*, xxii. 377, 1893 ; xxiv., 1895.

[2] *Phil. Mag.*, Jan. 1886.

[3] The law of the electrical reaction resulting in a generator from the mechanical motion is summed up in the well-known law of Lenz, that *the induced current is always such that by virtue of its electro-magnetic effect it tends to stop the motion that generated it.* In the converse case of the mechanical reaction resulting, in a motor, from the flow of electrical energy, it is easy to formulate a converse law, viz. *that the motion produced is always such that by virtue of the magneto-electric inductions which it sets up it tends to stop the current.*

Dynamos wound and connected for working as generators of continuous currents may be used in all cases as motors, but with some difference. A series dynamo set to generate currents when run right-handedly (and therefore having a forward right-handed lead), will, when supplied with a current from an external source, run as a motor, but runs left-handedly against its brushes. To set it right for motor purposes requires *either* that the connections of the armature should be reversed, *or* that those of the field-magnet should be reversed (in either of which cases it will run right-handedly), *or* else the brushes must be reversed and given a lead in the other direction (in which case it will run left-handedly). A shunt-dynamo set ready to work as a generator will, when supplied with current, run as a motor in the same direction as it ran as a generator; for if the current in the armature part is in the same direction as before, that in the shunt is reversed, and *vice versâ*. A compound-wound dynamo, set right to run as a generator, will run as a motor in the reverse sense, against its brushes if the series part be more powerful than the shunt, and with its brushes if the shunt part be the more powerful. If the connections are such (as in compound dynamos) that the field-magnet receive the sum of the effects of the shunt and series windings when used as a generator, then it will receive the difference between them when used as a motor. There are certain advantages in using a differentially-wound motor, as will appear hereafter.

The subject of alternate-current machines as motors is treated separately in Chapters XXIV. and XXV.

REVERSING GEAR FOR MOTORS.—A motor, as will be seen from the preceding discussion, can be reversed by the operation of reversing the current through the armature, and at the same moment reversing the lead. But reversing the current can also be accomplished by rotating the brushes through 180°. Consequently both these actions may be accomplished by the single operation of advancing the brushes through $180° - 2\phi$, where ϕ is the original angle of lead. But as the brush would then slant in the wrong direction, it is usual to provide a second set of brushes. This is, indeed, Hopkinson's method of reversing. He employs two pairs of brushes, each pair being capable of moving about a common pivot, so that either the pair having a lead in one direction, or the pair having a lead in the other direction can be let down upon the commutator. The result of this arrangement is that, by moving a lever, the angular lead and the direction of the current are reversed at the same instant. Such reversing gears are obviously most useful in the industrial applications of motors, and if the difficulties of sparking at the brushes caused by the sudden removals of them from the collector be obviated, must prove much better than any mechanical device to reverse the motion by transferring it from the axle of the motor through a train of gearing to some other axle. One great advantage of electric motors is, that they can be easily fixed directly on the spindle of the machine which they are to drive; an advantage not lightly to be thrown away. Carbon brushes are almost always used for motors, as their position end-on is suitable for revolution in either sense.

Various other forms of reversing gear have been proposed to accomplish the desired end. If the field-magnets of a motor are so powerful relatively to the armature that no lead has to be given to the brushes, the rotation can be reversed by reversing the polarity of either part. In Immisch's larger motors, the reversing-gear, which is very substantial, removes one pair of brushes and puts down at the same diametral points a second pair, reversed in position and polarity.

The form of brush shown in Fig. 248*c*, p. 320, is designed by Holroyd Smith for motor work, as it allows of rotation in either direction. So also do carbon-brushes, such as Fig. 249, p. 321.

Another mode of reversing was suggested by the author[1] in 1882. It is indicated in Fig. 335. It consists in joining one of the brushes to a point half-way along the field-magnet coils, which, though connected across the mains as a shunt, must not be of very high resistance. The current in the armature can then be reversed by simply switching the second brush from one main to the other. This principle is used in Maquaire's regulator for arc lamps, but is not suitable for large motors.

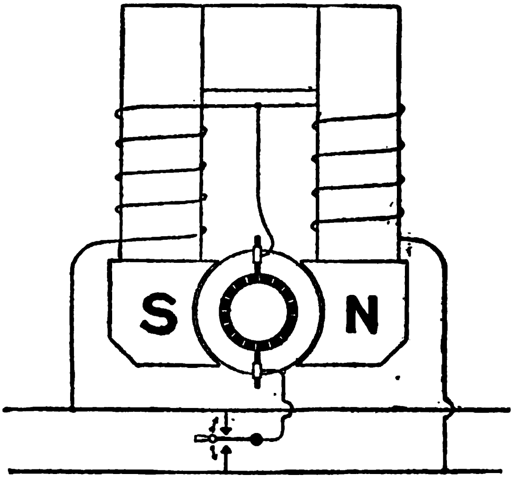

Fig. 335.—Electric Reversing Gear for a Motor.

GOVERNMENT OF MOTORS.

It is extremely important that electric motors should be so arranged as to run at a uniform speed, no matter what their load may be. For example, in driving lathes, and many other kinds of machinery, it is essential that the speed should be regular, and that the motor should not "race" as soon as the stress of the cutting tool is removed.

Interruptor Governor.—One of the earliest attempts to secure an automatic regulator of the speed was that of

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[1] Specification of Patent, No. 5122 of 1882.

M. Marcel Deprez, who in 1878 applied an ingenious method of interrupting the current at a perfectly regular rate by introducing a vibrating break into the circuit. The motor employed had a simple 2-part commutator, whose rotation timed itself to the makes-and-breaks of the current. This method is, however, inapplicable to large motors.

Centrifugal Governor.—Another suggestion, equally impracticable on the large scale, was to adopt a centrifugal governor to open the circuit whenever the motor exceeded a certain speed. A motor so governed runs spasmodically fast and slow.

It is also possible for a centrifugal governor to be employed to vary the resistance of a part of the circuit; for example, to work an automatic adjustment to shunt part of the current of a series machine from its field-magnets, or to introduce additional resistance into the field-magnet coils of a shunt-wound machine, in proportion as the speed falls. A case is shown in Fig. 336, in which a centrifugal governor driven by the motor alters the number of exciting coils in the field-magnet circuit, causing the magnetism to increase if the motor runs

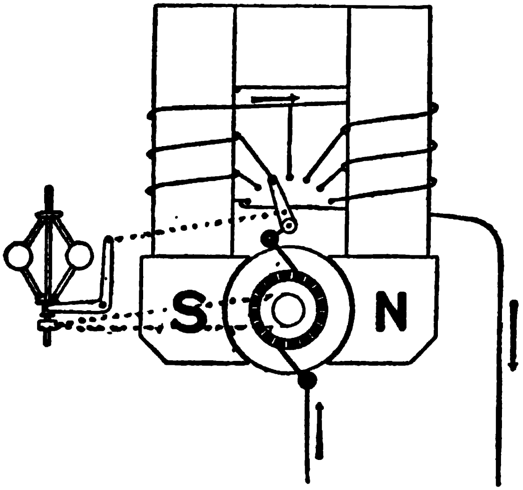

FIG. 336.—AUTOMATIC CENTRIFUGAL GOVERNOR.

too fast, and so brings down the speed again. This method was proposed by Brush, and answers well for motors in series in arc-light circuits.

Periodic Governor.—Ayrton and Perry proposed several forms of "periodic" centrifugal governor, a device by which in every revolution power is supplied during a portion of the revolution only, the proportion of the time in every revolution during which the power is supplied being made to vary according to the speed. As the main difficulty with such governors is to prevent sparking they are only applicable to very small motors. But there is a still more radical defect in all centrifugal governors: they all work too late. They do not perform their functions until the speed has changed.

Dynamometric Governors.—The author devised[1] another kind of governor which is not open to this objection. He proposed to employ a dynamometer on the shaft of the motor to actuate a regulating apparatus, consisting, either of a periodic regulator to shunt or interrupt the current during a portion of each revolution, or of an adjustable resistance connected in part of the circuit. The dynamometric part may take the form of a belt dynamometer (such as Alteneck's) or of a pulley dynamometer (such as Morin's or Smith's). In the latter case, which is the more convenient, a loose pulley runs on the motor shaft and is connected by a spring arrangement with a fixed pulley. The rotation of the motor will drag round the fixed pulley in advance of the loose pulley, and the angular advance will be proportional to the torque. The amount of such angular advance determines the action of the regulating part. The regulator in this case is therefore worked not according to the speed of the motor, but according to the load it is carrying. Any change in the load will instantly act on the dynamometric governor before the speed has time to change. If such a governor is purposely over-set it may even have the effect of causing the motor to run faster when the load comes on than it does when running idle.

Electric Governing.—Another method of governing, not requiring any rotating parts, has been proposed by the author. He uses as field-magnets a double set of poles, set at different angles with respect to the brushes of the motor. One pair of magnetic poles, having a certain lead, is actuated by series coils, the other pair, having a different lead, by shunt coils (see Fig. 265*c*). When both shunt and series are working, there will, of course, be a resultant pole having some intermediate lead. If the load of the motor is diminished it will tend to run faster, increasing the current in the shunt part, decreasing it in the series part, and therefore altering the effective lead and preventing the increase of speed.

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[1] Specification of Patent, No. 1639 of 1888.

In 1880 a motor was patented by André in which the field-magnets were wound in two separate circuits, one of thick and the other with thin wire, the current dividing betwen them, and the armature was connected as a bridge across these circuits as the Wheatstone's bridge. Motors governed on this principle were constructed about 1884, by Lieut. F. J. Sprague; they show remarkably good regulation.

The method of automatic regulation that is most perfect in theory is undoubtedly that of Professors Ayrton and Perry,[1] and is expounded in the following pages; it results in a differential compound winding.

THEORY OF SELF-GOVERNING MOTORS.

In the chapter on Self-regulating Dynamos, on pp. 224 to 242, were set forth the methods of solving the problem how to arrange a dynamo so that it shall feed the circuit with electric energy under the condition of a constant pressure, when driven at a constant speed. The solution to that problem consisted in the employment of certain combinations which gave an initial magnetic field due to a shunt coil, and an increment to that field dependent on the current that might be flowing in the main circuit.

Now it is not hard to see that this problem may be applied conversely, and that motors may be built with a combination of arrangements for their field-magnets, such that, when supplied with currents under the standard conditions of constant pressure in the mains, their speed shall be constant whatever the load. It will be evident, without any numerical calculations, that the windings must oppose one another—one must tend to magnetize the field-magnet, the other to demagnetize. Take the case of a shunt motor supplied at a constant potential $\mathcal{E}$, and running at a certain speed with a certain load. If the load is suddenly removed the motor will begin to race, its racing will increase the counter electromotive-force developed and will partly cut down the armature-current. But the decrease of current will not be quite adequate to bring back the speed, because of the internal resistance of the armature, which has prevented the whole energy of the armature current from being utilized as work. A demagnetizing series coil wound on the field-magnet will, however, effect what is wanted, for then, with any reduction of load, the corresponding reduction of current can take place, the resulting increase in the field-magnetism being sufficient to get the required larger counter electromotive-force without any increase in speed. For constant-current distribution no method of compound winding, whether differential or additive, has been found satisfactory; special regulators must be employed.

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[1] *Journal Soc. Telegr. Engineers*, vol. xii., May 1883; see also a later paper in *Phil. Mag.*, 1888.

The following synoptical table contrasts the arrangements for self-regulating generators with those of self-governed motors:

GENERATOR.	MOTOR.
Given Constant Speed.	*To get Constant Speed.*
To get e *constant.*	Given $\mathcal{E}$ *constant*
Initial magnetism { Steel magnets. Separate excitation. Shunt coils.	Initial magnetism { Steel magnets. Separate excitation. Shunt coils.
+ Series-regulating coils.	— Series-regulating coils.

In discussing the theory of the self-governed motor, we shall follow the same general lines as in discussing the theory of the self-regulating generator, namely, find an equation expressing the desired condition of constancy.

Shunt or Separately-excited Motor with Series-regulating Coil.—Using the same notation as previously, we have for the counter electromotive-force developed in the armature—

$$E = n\,Z\,\mathsf{N};$$

also

$$E = \mathcal{E} - (r_a + r_m)\,C.$$

Now N is made up of two parts, viz.:—N_1 the permanent part (which in a shunt motor is equal to $q\,S_s\,C_s$, where S_s is the number of windings in the shunt), and another part depending on the series coil which we may write $q\,S_m\,C$, where S_m is the number of windings in series and q has the same signification as on p. 229, and is equal to $4\,\pi$ divided by ten times the sum of the magnetic reluctances. Its value therefore depends upon the permeability, and therefore upon the degree of saturation of the iron of the magnetic circuit. Reserving this point for further consideration, we may write

$$\mathsf{N} = \mathsf{N}_1 - q\,S_m\,C.$$

If we had written + instead of —, we should find the solution coming out with the negative sign, indicating that the windings must be so arranged that the current in the series coil circulates in the negative or demagnetizing sense. We write the negative sign, however, as we already know that this must be so. We also assume at present that there are no armature reactions. Substituting the value of N in the fundamental equation, we have

$$E = n\,(Z\,\mathsf{N}_1 - Z\,q\,S_m\,C);$$

and equating this to the other value of E in the second equation above, we find

$$n = \frac{\mathcal{E} - (r_a + r_m)\,C}{Z\,\mathsf{N}_1 - Z\,q\,S_m\,C}. \qquad \text{[I.]}$$

Having thus obtained an expression for the speed, we must examine the various parts of the expression to see which are variable and which constant, and so deduce a relation which shall make n constant. Now in both numerator and denominator there are two terms, the first of which is a constant, whilst the second of each contains the variable C. A little consideration will show that the fraction cannot have a constant value unless the two coefficients of the variable in the second terms bear the same ratio to one another as do the two constants which stand as the first term; or n cannot be constant unless

$$\frac{\mathcal{E}}{Z N_1} = \frac{r_a + r_m}{Z q S_m},$$

or

$$\frac{\mathcal{E}}{N_1} = \frac{r_a + r_m}{q S_m}, \qquad \text{[II.]}$$

which is the desired equation of condition.

If this condition be observed (and it will be noted that the quantity of series winding required is proportional, as in the self-regulating dynamo, to the internal resistance of the machine), then the speed will be constant and of the value

$$n = \frac{\mathcal{E}}{Z N_1} = \frac{r_a + r_m}{Z q S_m}. \qquad \text{[III.]}$$

From the first of these relations we see that the speed at which the machine is thus governed to run is the same speed as that at which, if driven as a generator on open circuit, it will yield an electromotive-force equal to that of the supply at the mains. When running as an unloaded motor, it ought of course to turn so fast as to reduce the current through its armature to a minimum, which it can do by running at this speed. It is evident that by making the permanent part of the magnetism strong enough, the critical speed—that is to say, the speed for which the motor is self-governing—may be made as low as desired. As the load on the motor is increased, the flow of current through the armature must be increased, and this increased current cannot flow unless in some way the counter electromotive-force of the armature be diminished. As the speed is to be kept up, this is accomplished by the lowering of the magnetism, which occurs in consequence of the increased current flowing through the demagnetizing coils. The quantity denoted by q, which depends on the permeability of the iron, may be taken at an average value between the two extremes which it has at maximum load and at zero load, since in a well-designed motor the resistances in the armature-circuit are very small, and the efficiency as a whole high, the demagnetizing effect of the series coils, even at full load, need only reduce the magnetization by a small percentage. Moreover, with the backward lead given to the brushes to prevent sparking, the armature itself will act partially as a demagnetizing series coil, and so compensate for alteration in the permeability. The magnetism is a maximum when the motor is running empty. When the load is greatest, if the motor is running at, say 80 per cent. efficiency, E will be 80 per cent. of $\mathcal{E}$; that is to say, N will be 80 per cent. of N_1. It is between these limits in the magnetization that the value of q must be averaged. It is evident from equation [III.] that if the motor is already provided with a given series winding, there can be found a value of $\mathcal{E}$, for which the condition of self-governing can be still fulfilled. In the case of a shunt motor, the above equation is capable of further simplification; for we know that $\mathcal{E} = C_s r_s$, where r_s is the resistance of the shunt, and $N_1 = q\ S_s\ C_s$. Substituting these values in [II.] above, we get

$$\frac{S_s}{S_m} = \frac{r_s}{r_a + r_m}. \qquad \text{[IV.]}$$

which is Ayrton and Perry's rule for the winding of the self-governing motor. Motors wound differentially in the proportion indicated in equation [IV.] are very nearly self-governed. Some excellent motors by Sprague were wound according to this rule. One very curious property of this method of winding is as follows:—Suppose the motor to be standing still and the current turned on, the ampere-turns due to the shunt will be equal to $\mathcal{E}\ S_s \div r_s$, whilst those due to the series coil will be $\mathcal{E}\ S_m \div r_a \times r_m$; and these, according to equation [IV.], will be equal, and they are of opposite sign. There should then be no magnetism excited at all. But if there is any lead at the brushes, the magnetizing tendency of the armature will come into play; and if the brushes have a considerable negative lead, the effect will be to magnetize the field-magnet in the wrong sense, and then the motor starts the wrong way. The defect might be remedied by cutting out the series coil or reversing it, until the motor has got up its speed. The latter course is preferable, as the additional torque of the series motor is of great advantage in overcoming the statical resistance to motion experienced at starting.

It is obvious that the number of shunt-turns should theoretically be such that the motor, driven on open circuit at the given speed, shall generate an electromotive-force equal to $\mathcal{E}$.

Practical Determination of the Shunt and Series Windings.[1]—As in the case of compound windings of dynamos (p. 238) so for motors, the proper windings can be found by simple experiments, a temporary coil being wound and separately excited, and a resistance equal to the future r_m being added to the armature resistance. Two experiments are required. Run the motor first with no load at the brake, using the proper pressure V, and excite the temporary coil, observing the number of ampere-turns that are needful to bring the speed down to the required n. The number of ampere-turns in this case is equal to $S_s C_s$, where C_s is the current, which economy dictates should be used in the shunt. Secondly, run the motor with the fullest load at the brake, and again excite the field-magnet with such a number of ampere-turns that the speed is constant at n. From this and the previous experiment S_m can be calculated.

The efficiency of a differentially-wound motor cannot be expected to be quite as high as that of one which is not differentially wound, since the energy expended in the former case in magnetizing the field-magnets is greater relatively to the amount of magnetization produced.

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[1] It should be pointed out that this process differs from that suggested by Professors Ayrton and Perry in their paper on electromotors, in *Journal Soc. Teleg. Engineers*, May 1883. Their method depends on the volume left on the bobbins of the field-magnets, which is assumed to be constant.

MECHANICAL CHARACTERISTICS OF COMPOUND DIFFERENTIAL MOTORS.

It may be convenient here to consider the graphic representation of the regulations between speed and torque in motors provided with mixed windings.[1]

The curves for constant-potential supply are shown in Fig. 337. The letters M and S refer to main circuit windings and shunt windings respectively. The forms of the curves for mixed windings differ somewhat according to the proportions of the two sets of coils. The important case is that of the differential winding marked S — M, having a few series turns to correct the droop of the pure shunt-winding, and it will be noted that up to a certain limit the speed is nearly constant, but that there is a maximum value to the torque. In the case of constant-current supply, as the curves of Fig. 338

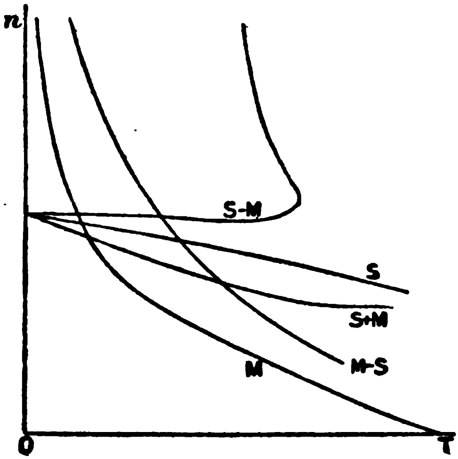

FIG. 337.
MECHANICAL CHARACTERISTICS AT CONSTANT POTENTIAL.

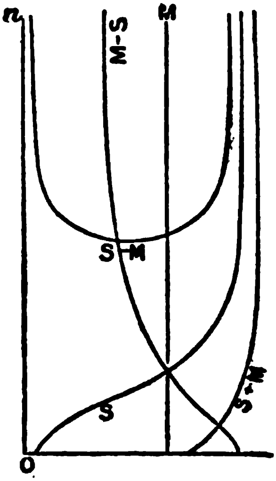

FIG. 338.
MECHANICAL CHARACTERISTICS WITH CONSTANT CURRENT.

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[1] The author is indebted to Frölich's *Die Dynamoelektrische Maschine* for the curves of motors with mixed windings. Similar curves have been deduced by Rechniewski, see *Séances de la Société de Physique*, 1885, p, 197.

show, the only winding which gives any approximation to a constant speed is the differential winding with large shunt and small series coil. For, as in the case of the constant-current generator, the variation of the magnetism has to be carried through an enormous range, defying any averaging of the magnetic permeability.

An elegant graphic method of treating the problem of self-government of motors is given by M. Picou in *La Lumière Électrique*, xxiii. 114, 1887.

Shunt Motor.—It was observed by Mr. Mordey,[1] that if a pure shunt motor is constructed upon perfect designs—that is to say, having very small resistance of armature and very large resistance of shunt, and having also field-magnets, which are very powerful relatively to the armature, and an armature properly laminated and sectioned so as to reduce eddy-currents and self-induction to a minimum—such a shunt dynamo, if supplied from mains at a constant potential, will run at a nearly constant speed whatever the load.[2] The slight demagnetizing action of the armature when a negative non-sparking lead is given to the brushes acts, in fact, instead of any special demagnetizing coil. The following tests showed a constancy to within 1½ per cent. for all loads within working limits.

Potential at Terminals.	Current (amperes).	Horse-power at Brake.	Revolutions per Minute.	Torque (pound-feet).
68·4	44	1·1	1125	5·15
68·4	126	7·4	1120	33·4
68·4	165·5	10·36	1115	48·8
68·4	180	11·14	1110	53·0

With a lower electromotive-force the same motor regulated almost equally well, but at a lower speed. It was observed that, especially when the motor was giving out small horsepower, the speed was increased by weakening the field.

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[1] See *Phil. Mag.*, January, 1886.

[2] This might have been foreseen from the equations of p. 525, in which if $r^a + r^m = 0$, the condition of regulation will give $S_m = 0$.

Other Methods of Governing Motors.—A further suggestion for governing motors is due to Mr. Mordey and Mr. C. Watson. They wind the armature with two windings, having separate commutators. One winding—the main one—is the ordinary armature circuit of the motor, and is supplied with current from the external source, causing the armature to revolve. The other winding, which may be called the regulating armature winding, is small in amount, and is disposed over, or side by side with, the main motor-winding. This additional winding is not connected to the mains or source of current, but to the field-winding by means of a special commutator or collector and brushes. It will be observed that this additional armature-winding, revolving in the field, constitutes a generator of current. The regulating action is as follows:—When a tendency to increase in speed results from a diminution of the load, the additional armature-winding tends to increase the strength of the field by supplying more current to the field-coils, and thus raises the opposing electromotive-force of the motor, diminishes the amount of current received from the mains, and so reduces the speed to its normal rate. Again, an increase of the load, tending to reduce the speed, is counteracted by a lessening of the magnetizing current produced by the additional winding, a consequent lowering of the opposing electromotive-force of the motor, and an increase of the current received from the mains. It will be seen that as this plan is summative it does not require so great an expenditure of energy in the fields as a differential winding ; nor is it open to the objection that the motor may start in the wrong direction. On the other hand, it has the drawback of requiring an additional commutator. The method has given very good results.

A possible mode of governing constant-current motors is by providing a variable magnetic shunt, in the converse of the manner suggested by Trotter for constant-current generators. Various other modes[1] of controlling the speed by altering the magnetism have been suggested, but few of them are automatic or reliable.

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[1] See a most interesting and fully illustrated paper by F. B. Crocker in *Electrical World*, xiii. 311, 1889.

CHAPTER XXI.

MODERN FORMS OF CONTINUOUS-CURRENT MOTORS.

ALMOST any good modern dynamo (independently excited, shunt wound, or compound wound) will serve as a motor on mains supplied at the proper pressure; but attention has to be paid to the setting of the brushes that it may run rightly, and the machine so used must be one that will give the proper voltage at the proper speed. In designing motors precisely the same principles hold good[1] as obtain for designing generators; for the same features, namely, low internal resistance, powerful field-magnets, and proper elimination of eddy-currents, which go to make a good generator, also apply to the making of a good motor. For example: suppose it is desired to design a 10 H.P. motor to run at 500 revolutions per minute, when supplied from 200 volt mains. Now 10 H.P. is 7460 watts; a motor to give out actually 7460 must be allowed to absorb (at 85 per cent. nett efficiency) 8776 watts. Further, if its electrical efficiency is to be, say 90 per cent., it must generate 180 volts of counter electromotive-force. Dividing 8776 watts by 180 volts we find 48·75 amperes as the current it must take at normal load. If, therefore, we simply set to work to design a dynamo with good powerful field-magnets capable of generating 50 amperes at 180 volts, at a speed of 500 revolutions per minute, we shall have obtained what we wanted.

Snell has given the following rules for expressing the actual H.P. which may be safely and continuously taken from continuous-current motors:

Ring armatures, 2-pole; $\text{H.P.} = 0{\cdot}00001 \times l\, d^2\, n$,
Drum armatures, 2-pole; $\text{H.P.} = 0{\cdot}000015 \times l\, d^2\, n$;

---

[1] For discussion of the subject of motor design, see a paper by Snell in *The Electrician*, xxii. 318 and 403, 1889; also *Journ. Inst. Electr. Engineers*, xx. 1891.

where l is length of armature and d its diameter, in inches, and n the revolutions per minute.

It might be supposed from the opening statement that any description of motors was superfluous. There are, however, certain special forms of machine that have come into notice as motors, and are, therefore, described here.

Amongst the motors which were at one time in commerce were special forms by Ayrton and Perry, with a fixed external ring armature and an internal revolving field-magnet. They possessed the structural defect of possessing too weak a field-magnet to enable them to run sparklessly, and though remarkably compact and convenient, fell into disuse. These motors were illustrated in the earliest editions of this book. A little later excellent forms up to several horse-power were constructed by Reckenzaun, Immisch and others, which were also noticed in former editions. Reckenzaun conceived the useful notion of winding the magnets of a series motor for traction purposes with two, or in some cases three, coils on each limb, which might be put in parallel or series so as to vary the exciting power and permit of obtaining the different rates of speed and power required in tramway work without resorting to artificial resistances, and also of obtaining a great torque in starting, when all the coils are in series.

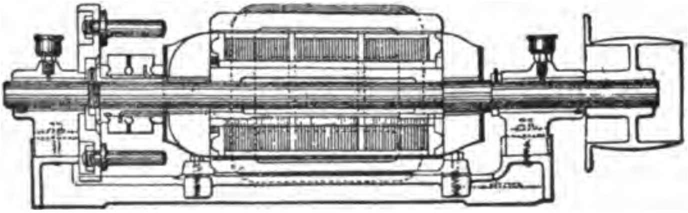

FIG. 339.—IMMISCH'S MOTOR (Section).

Immisch's motors were amongst the first in England to be well and mechanically constructed. The armature cores were built up of insulated disks, having at the ends, and at intervals, thicker disks provided with projecting driving-teeth, all the disks being securely keyed to the shaft. The windings were insulated with Willesden paper protected with india-rubber varnish. In the commuting arrangements special means were taken to cut out the coils as they reach the neutral point; the effect, according to the inventor, being to diminish cross-magnetizing influences and obviate changes of lead.

In Immisch motors carbon brushes, Fig. 249, p. 321, are used. The mode of driving the core-disks of the large machines is shown in Fig. 224, p. 294.

A 30-H.P. motor, designed by Mr. A. T. Snell, for mining purposes,[1] weighing 850 kilogrammes, gave the following results:—

Revolutions per Minute.	Volts.	Amperes.	E.H.P. absorbed.	H.P. given out.	Efficiency.
660	500	49	33	29·8	·90
680	500	48	32·2	29·5	·91
675	500	49	33	29·5	·89

A number of firms—for example, Messrs. Cuttriss of Leeds, M. Trouvé of Paris, and Messrs. Crocker and Wheeler, in New Jersey—have made a speciality of small motors for driving fans, lathes and other light running machinery.

All large firms who construct continuous-current dynamos, furnish them also as motors, in some cases making special patterns, the only difference being that a machine designed for a motor usually has the field-magnet carried to a rather higher degree of saturation, and made relatively more powerful than in the corresponding size of dynamo. If two machines are to be used together as generator and motor, the former being driven at a constant speed, the latter will not run at a constant speed at all loads if they are of identical construction, for the voltage given to the motor falls as the current in the line increases. To make the motor run at constant speed it should be wound with fewer armature conductors in proportion precisely to the efficiency contemplated.

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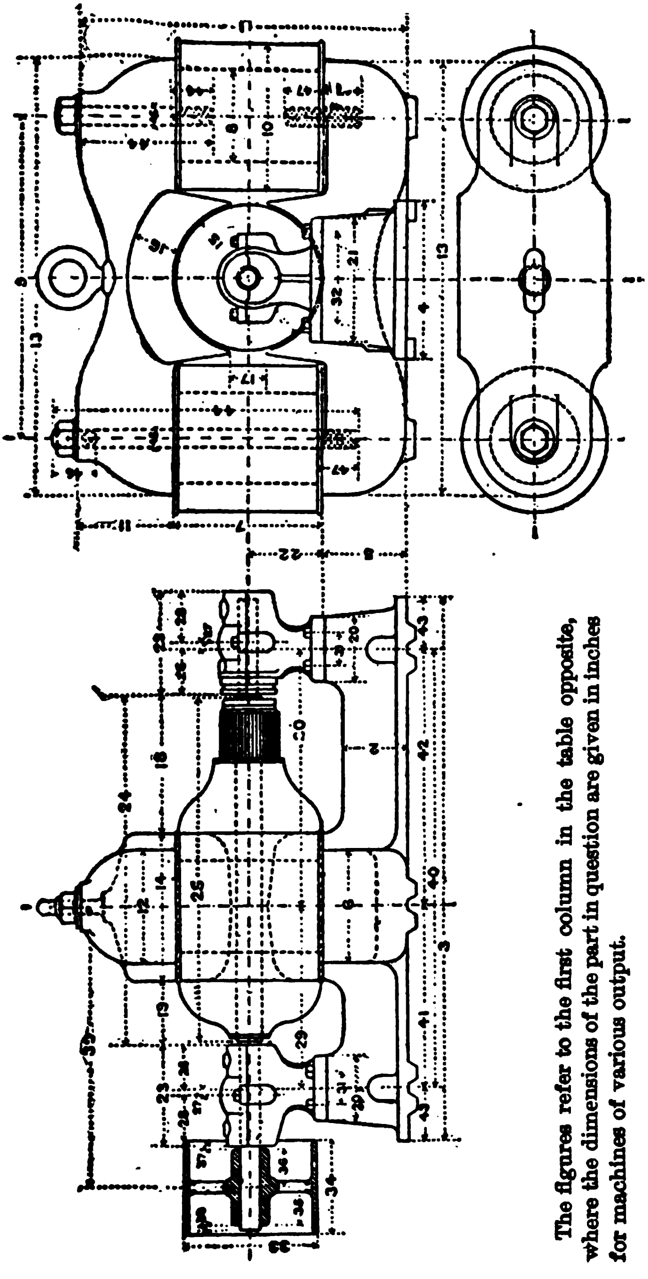
[1] See notes by Mr. Snell on Electrical Work in Mines, in *Proc. South Wales Institute of Engineers*, July 27, 1891. Also lecture on *Electricity in Mining*, by author of this book, published by Messrs. Spon.



The figures refer to the first column in the table opposite, where the dimensions of the part in question are given in inches for machines of various output.

Fig. 340.—Sprague's Motor.

TABLE OF DATA OF SPRAGUE MOTORS.

(The figures in the first column refer to dimensions indicated in Fig. 340).

Motor H.P.		1	2	3	5	10	15	20	25	35	50	75
Total height	1	11¾	13⅞	15 7/16	17¾	20⅝	22⅞	25⅛	28	33⅞	38⅛	48⅛
Height of bed-plate ..	2	2⅜	2⅝	3	3⅜	4	4⅜	4⅜	5⅜	7⅜	8⅜	9
Length of bed-plate ..	3	19⅜	22⅝	26⅜	28⅜	31½	37⅝	40	45⅝	57⅝	64⅝	73⅛
Width of bed-plate ..	4	5¾	6⅜	7½	8	8⅞	9½	10⅛	12½	13⅜	14⅝	19
Height of core-seat ..	5	3	3⅛	3⅜	4⅛	5	5⅛	5⅜	6⅛	7⅞	10	13½
Diam. of core-seat ..	6	4	4⅞	5⅛	5⅞	7⅝	8⅛	9⅛	10⅝	13⅛	14⅝	17⅛
Length of core	7	5⅝	6⅝	7 3/16	8¼	9⅜	10⅝	11⅜	13	15½	17½	19⅞
Diam. of core	8	3⅛	3⅞	4⅜	4⅝	6	6 11/16	7⅞	8⅛	10⅝	11⅝	13⅛
Between core-centres	9	12⅛	14½	16⅝	19¼	22⅜	24⅞	26⅛	30⅛	32¼	36⅝	43⅝
Diam. over winding ..	10	6⅝	6¾	8	9⅛	10½	12	12⅝	14½	15½	17¼	20½
Height of keeper ..	11	3	4	4⅛	5	6½	7	7⅞	8⅛	9⅞	11	15
Width of keeper ..	12	4	4⅞	5⅛	5⅞	7⅜	8½	9½	10½	13⅛	14⅝	17⅛
Length of keeper ..	13	16⅛	19⅜	22½	25	29⅞	33⅜	35⅞	40⅝	45⅞	51⅛	60⅝
Length of field	14	5½	6½	7	8	9⅛	10⅜	11⅜	12⅜	14½	16	18⅛
Bore of field	15	5⅝	6⅝	7 3/16	8¼	9⅜	10⅝	11⅜	13	15½	17½	19⅞
End thickness, pole-piece	16	1¾	1⅞	2	2½	3	3½	3⅜	3⅜	3⅝	3¾	4
Space between pole-tips	17	1⅜	1½	1⅞	2⅜	2 7/16	2⅜	3½	3⅜	4⅜	5⅜	5
Block to fields (comm. end)	18	5	5⅞	7⅜	8 3/16	8⅝	11 5/16	11 5/16	12½	17 9/16	19⅜	20⅜
Block to fields (pulley end)	19	2⅛	2⅞	3⅜	3 5/16	3 9/16	4 1/16	4 1/16	5	8 11/16	9	10⅜
Length, pillow-block seat	20	2⅜	2⅜	3	3½	3⅜	3⅜	4½	5	5⅛	6	7
Width, pillow-block seat	21	4½	5½	6	6⅛	7⅜	7⅜	9	10	11	12	12½
Height of pillow-block	22	2 11/16	3 5/16	3 13/16	4⅛	4 11/16	5 3/16	5⅞	6⅛	7⅝	8⅝	11½
Length of pillow-block	23	3⅜	4½	4½	5¼	6	6⅝	7⅜	8½	10	11⅝	14½
Between shaft shoulders	25	12 7/16	14 13/16	18 7/16	19¾	21 3/16	25⅝	26⅛	30⅜	40⅝	45⅛	51 3/16
Diam. of pulley	33	4½	5	6	8	9	10	11	12	16	20	24
Face of pulley	34	2½	3	3½	4	6	7	8	10½	12	12	13
Length of hub	35	2½	2¾	3	3	3⅜	4⅜	5½	6	9	9	9
Between centre of motor and centre of pulley	39	9 13/16	11 13/16	13 7/16	14½	16 3/16	18½	20⅜	23⅜	30⅜	32⅜	38 11/16
Length of core bolts ..	44	11⅛	13½	14⅝	16½	19½	21⅝	23⅜	25⅛	13	14¾	21
Diam. of core bolts ..	45	5⅜	¾	⅞	1	1⅛	1½	1¼	1½	1	1⅜	1⅜
Diam. of core disks ..	48	4¾	5 13/16	6 5/16	7⅛	8⅛	9⅜	10⅜	·11 11/16	14⅛	16	18⅛
Diam. of armature ..	49	5½	6½	7 1/16	8⅛	9½	10⅛	11⅝	12⅞	15 1/16	17 1/16	19⅝
Armature conductors (at 110 volts)	50	768	432	432	348	..	..	..	..	..	..	..
Armature conductors (at 220 volts)	50	1680	1248	900	696	576	352	320	320	..	..	..
Armature conductors (at 440 volts)	50	..	..	..	..	1080	704	640	600	464	420	388
Segments in commutator	51	24	48	36	58	48 90	88	80	80 100	58	70	97
B in core disks ..	52	3820	3770	4090	4040	4770	4720	4740	4240	8100	7030	7720
N (useful) megalines ..	53	·489	·701	·924	1·228	1·800	2·413	2·974	3·274	8·517	9·353	13·943
Total ampere-turns ..	54	5298	7746	8192	12043	11535	14814	17453	22475	28138	24973	31700
Revolutions per min. ..	55	1750	2000	1650	1550	1360	1500	1350	1350	675	665	485

For instance if the electrical efficiency of the transmission is to be 85 per cent. the motor armature should have 85 per cent. of the number of conductors that there are in the generator armature. As an example see Brown's 240 H.P. motor mentioned on p. 412.

Sprague's Motors.—Several firms have made a speciality of motor work. Amongst American engineers, Lieut. F. J. Sprague was early in the field with several forms of motor of excellent design and construction; many hundreds of them were in use in the States for lifts, machine tools, and the like, until his firm was amalgamated with the Edison Co., after which time the Edison bipolar dynamo was substituted. One form of these machines, resembling the "Manchester" type of dynamo, is shown in Fig. 340. Sprague's method of winding the field-magnets with a differential compound winding is identical with that invented in 1883 by Ayrton and Perry, depending upon the use of a coil in series with the armature to demagnetize and weaken the field.[1] Many other ingenious methods of governing and practical applications have been worked out by Sprague. The reference numbers given in Fig. 340 relate to the statistics given in the accompanying table, from which the relative sizes of a well-worked-out line of machines can be learned. For further details the reader is referred to the accounts published in the technical press.[2]

Crocker and Wheeler's Motors.—Another American firm that has been very successful with motors, particularly in small sizes, is that of Crocker and Wheeler, of Ampere, N.J.

Fig. 341 gives a general view of the bipolar motor of this firm. The magnet limbs are stamped in one piece out of wrought iron or mild steel, and set firmly in the cast-iron bed. The armature is built up of toothed core plates (see Fig. 212, p. 287) and ring wound, the finished armature being represented in Fig. 342. A starting gear is usually provided with these motors, consisting of a switch, with resistances, so arranged that the field-magnet is first excited, the armature then thrown into circuit with a resistance which, when the motor acquires speed is cut out by a further movement of the starting switch. For use in arc-light circuits[1] a centrifugal governor is added to the shaft. For sizes up to 10 H.P. the bipolar type is used, but for large sizes 4-pole designs of the type of Fig. 278 are preferred.

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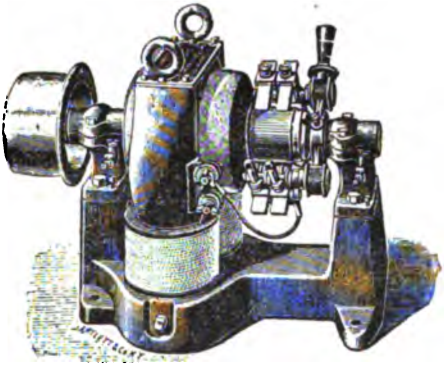
[1] See Specifications of British Patents, Nos. 15,768 of 1884, and 3524 of 1885.

[2] *Electrical World*, October 1886; also Martin and Wetzler's treatise on *The Electric Motor*, 157-75; and *Electrical World*, xiv. 3, 1889; xv. 370, 1890; also *Electrician*, xxiv. 248, 1890.



FIG, 341.—CROCKER-WHEELER MOTOR.

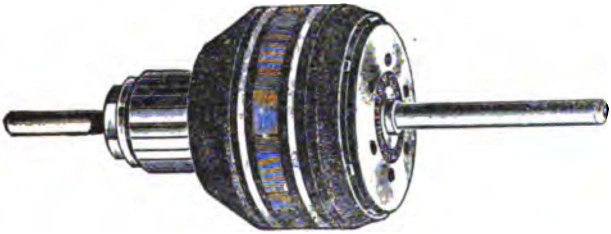


FIG. 342.—ARMATURE OF CROCKER-WHEELER MOTOR.

The following table gives some statistics about these machines.

For further accounts of the Crocker-Wheeler motors, and

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[1] For some accounts of motors for constant-current circuits, see *Electrical World*, xv. 269, 1890; xvii. 120 and 130, 1891; also *Electrician*, xxv. 16, 45 and 131, 1890.

CROCKER-WHEELER MOTORS.

Output.	Revolutions per Minute.	Weight, Lbs.	Armature Diam., Inches.	Commutator Parts.	Core Teeth.
Bipolar.					
$\frac{1}{12}$	1900	17	3	12	0
$\frac{1}{6}$	1800	26	3·601	16	8
$\frac{1}{4}$	1400	70	4·75	24	12
$\frac{1}{2}$	1250	106	5·625	24	12
1	1000	201	7	32	16
2	1000	281	7·75	48	24
3	950	364	8·75	48	24
5	950	590	9·187	56	28
10	875	1065	11	56	28
Four-Pole					
15	850	1450	11	102	51
30	750	2800	15	110	55

their application to driving workshop tools, the reader is referred to the technical journals.[1]

A.E.G. Motors.—In Germany the Allgemeine Elektricitäts Gesellschaft has made a specialty of small motors, both for continuous current and alternating. Their typical form up to 12 H.P. is shown in Fig. 343. For larger outputs 4-pole and 6-pole machines are used. This company has long systematized its manufactures. The following table includes the usual sizes.

H.P.	$\frac{1}{16}$	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{2}$	1	1·5	2·5	4	6	10	20	30	40	60	90
Revs. per minute.	1600	1100	2100	1900	1650	1480	1270	1100	1020	925	850	720	650	600	450
Total wt., kilos.	30·5	50·5	55	75	120	220	355	385	520	825	1820	2370	2980	4100	4760
Amperes at 105 volts.	1·3	2·5	2·9	5·0	9·5	14·4	22·2	34·3	50·8	82·9	170	255	355	510	700

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[1] See *Engineering*, xliv. 83, 1887; also *Electrical World*, ix. 4, 9 and 203; xiii. 309, 1889; xv. 114, 269 and 370, 1890; xvii. 130, 191. Also see Professor Crocker's book, entitled 'Practical Management of Dynamos and Motors,' and a series of papers by Professor Crocker in *Elec. Engineer* (N. Y.), 1891 and 1892.

Goolden's Mining Motor.—Mr. Atkinson has designed for Messrs. Goolden & Co. a mining motor of the simple bipolar

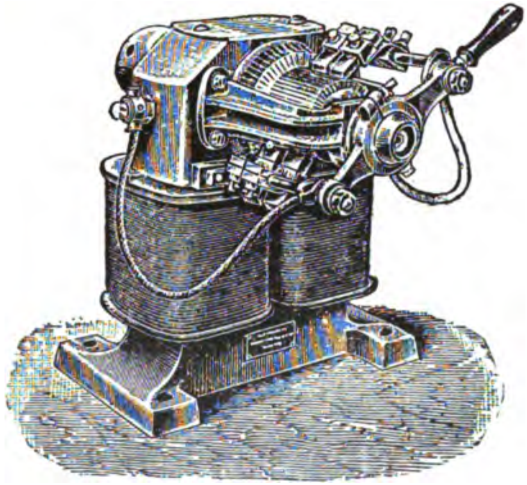

FIG. 343.—A.E.G. MOTOR.

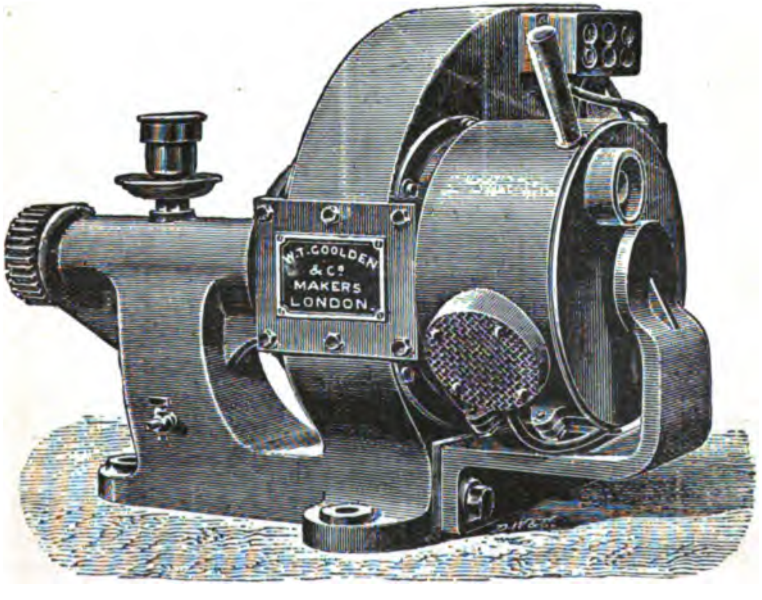

FIG. 344.—GOOLDEN ENCLOSED MINING MOTOR.

type, with special adaptations for use in coal-mines;[1] the moving parts being enclosed so that all possibility is removed of a spark at the brushes causing an explosion. As shown in Fig. 344, the commutator and brushes, which are of carbon, are completely boxed in.

Sayers' Mining Motor.—An entirely-enclosed mining motor, having fixed brushes and compensating armature on Sayers' design, has been introduced by Messrs. Mavor and Coulson. Fig. 345, which gives a section of this machine, shows the position of the auxiliary poles P^2, the use of which was described on p. 395. A 30-kilowatt motor, running at 700 revolutions per minute, weighs 3732 lbs. complete. The core-disks are deeply slotted with 4 main conductors and 3 commuting conductors in each of the 108 slots. The armature body is 9½ inches long, and 17½ in diameter.

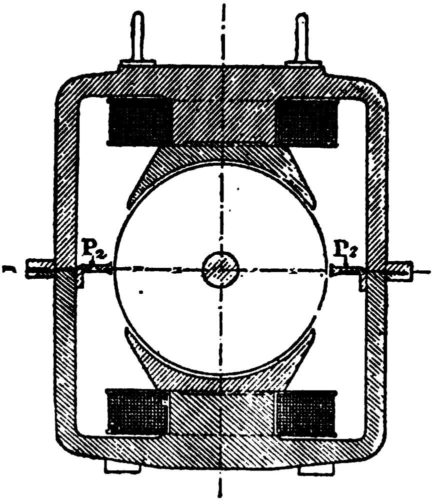

FIG.—SAYERS' MINING MOTORS.

Electric Locomotive Motors.—Many motors have been designed for propelling tramcars and for electric railways; the points that inventors have chiefly considered being strong mechanical design of armature, slow speed with or without gearing, and construction that will resist deterioration, by water, mud, dust, or overheating. Owing to the enormous rush of current just at starting, the armature must be capable of enduring the severest torque, and be practically fireproof as well as waterproof. For tramcar driving a single-reduction gear has found general favor, but for heavy railroad work all gearings for speeding down have gradually fallen into disfavor, direct-driving slow-speed forms being more reliable. All this implies the employment of motors with relatively powerful field-magnets. This is not the place to enter on a detailed account of electric locomotion in general, or to describe any of the hundreds of electric tramways and railways now running. Suffice it to say that the lighter street-tramway systems have developed to an enormous extent in the United States, where alone more than 10,000 miles of electric street lines are at work, mostly with an overhead trolley-system of supplying current to the cars. The usual pressure is 500 volts. Generators suitable for such systems are described on p. 433. With respect to the motors, apart from the difficulties arising from damp, dirt and vibration, the main difficulty lies in designing the magnet,

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[1] See the author's *Electricity in Mining*, p. 38, for descriptions of electric coal-cutters and other mining appliances.

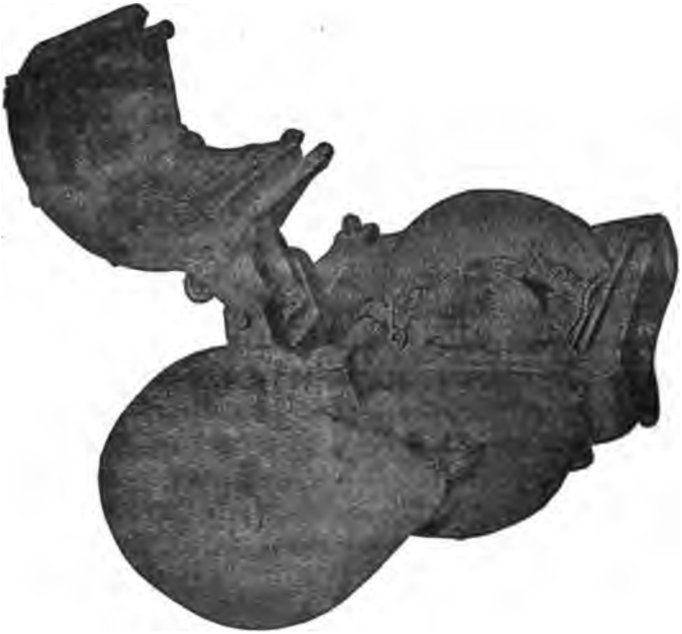
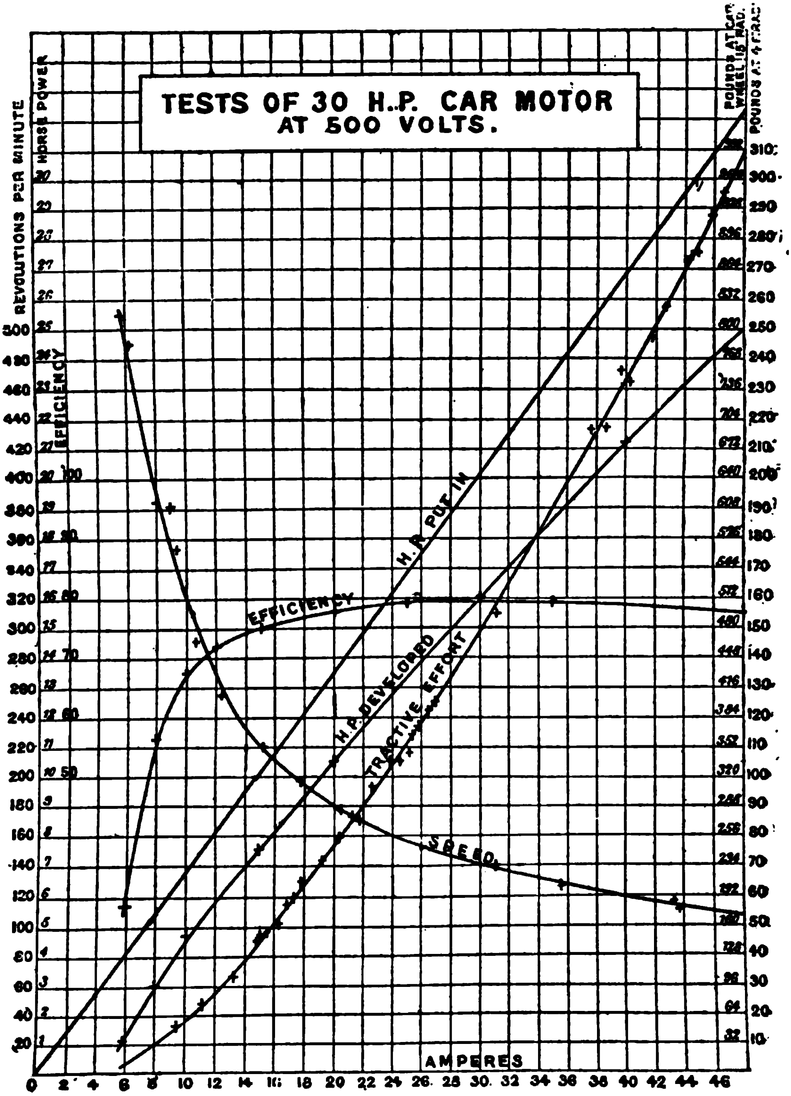


FIG. 346.—MAGNETS FOR STREET-CAR MOTOR.

which must be both powerful and very compact. An early form used in the States resembled No. 32, Fig. 103, p. 163, but inverted.[1] More modern forms have four poles with very



Tests of 30 H.P. Car Motor (Westinghouse Co.).

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[1] See *The Electric Railway*, by O. T. Crosby and Louis Bell (New York,) 1892.

TEST OF A 30 H.P. WESTINGHOUSE STREET-CAR MOTOR.

Current	3½	10	20	30	40	50	60	70	80	90	94
Revs. of car axle	479	236	145	118	99	85	72	61	50	39	35
Torque (nett in lbs.-foot armature)	0	29	95	183	281	387	494	510	731	863	912
H.P. on brake	0	3·9	9·1	13·9	17·7	20·9	23·8	24·2	24·0	22·1	20·9
H.P. supplied electrically.	2·05	6·0	12·05	18·1	24·15	30·2	36·2	42·25	48·27	54·29	56·7
Electrical efficiency ..	98·5	96	91·5	86·8	81·3	76·2	70·5	63·0	54·5	45·0	40·5
Commercial efficiency	0	65	75·7	77	74	69·2	63·6	57·4	50·2	41·5	36·8
H.P. lost in copper ..	·028	·24	1·05	2·43	4·45	7·24	10·62	15·77	21·99	29·58	32·6
H.P. lost in iron, gearing, etc.	2·02	1·86	1·90	1·77	2·00	2·06	2·28	2·28	2·31	2·61	3·2
Ampere turns per pole	626½	1,790	3,580	5,370	7,160	8,950	10,990	12,530	14,320	16,110	16,825
Ampere turns in gap ..	500	1,600	2,900	3,400	4,060	4,500	4,950	5,200	5,500	5,750	5,850
B„ in gap	15,000	30,000	46,200	54,000	60,600	66,000	72,000	76,200	80,400	84,000	85,200
B„ in pole	14,400	28,800	44,400	51,600	60,200	63,000	69,000	72,600	76,800	79,200	81,600
B„ in armature	15,600	31,200	48,600	56,400	63,000	69,000	75,600	79,200	84,000	87,600	88,800
B„ in teeth.	24,000	47,400	73,200	85,800	95,400	103,800	114,000	120,000	126,600	132,600	134,400

The dimensions of parts are as follows:—Armature, length, 15 inches; diameter, 11⅝ inches; diameter of bore, 12$\frac{1}{16}$ inches; length of bore, 14 inches; core disks with 95 slots, $\frac{3}{16}$ inch wide, 1 inch deep; 8 wires per slot, No. 11 B. and S. gauge. Total area of teeth, 280.5 sq. inch. Commutator, 8⅜-in. diameter, 2$\frac{5}{16}$-inch face. Brushes, carbon, 2¾ inches long, 2$\frac{5}{16}$ wide, $\frac{7}{16}$ thick; sectional area, 1 sq. inch. Area of pole face, 75 sq. inches; section of pole piece, 73 sq. inches; area of yoke, 21 inches by 1½ inch. Lengths of magnetic paths: armature, 6 inches; teeth, 2 inches; gap, $\frac{7}{16}$ inch; yoke, 25 inches. Sectional areas for magnetic lines: armatures, 134 sq. inches: teeth, 88·6 sq. inches; gap, 140 sq. inches; yoke (to carry half the flux), 73 sq. inches. Field winding, 179 turns per coil, 4 in series, No. 6 B. and S. gauge. Gear-ratio, 62 to 18.

short cores, with an arrangement for hinging the yoke-frame in two parts as shown in Fig. 346. The armatures of these motors are those represented in Fig. 217 in act of being wound. Fig. 347 gives other views of motor armature construction, and on p. 542 are given graphically the results of some tests of a 30 H.P. street-car motor of the Westinghouse Company when supplied at 500 volts. It will be seen that the efficiency is close to 80 per cent. In the table on p. 543 are given some data respecting another test of the same motor when run at 450 volts.

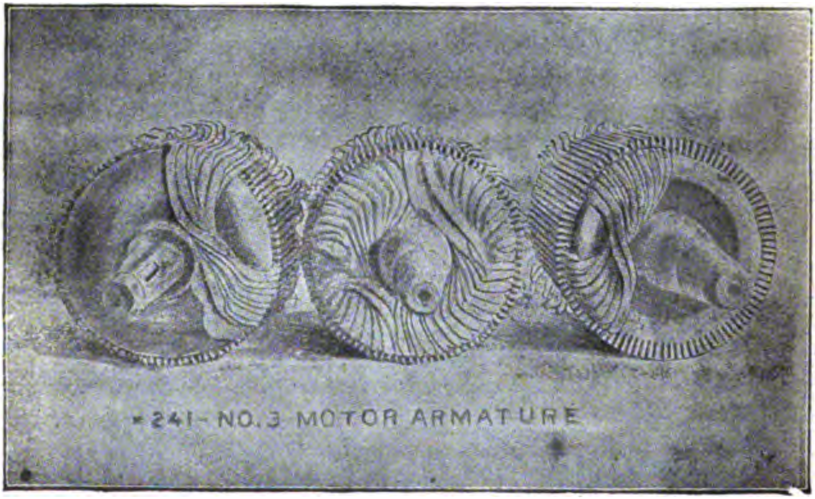

FIG. 347.—ARMATURES IN PROCESS OF CONSTRUCTION.

For tramway work Messrs. Mather and Platt make a standard type of single-reduction geared motor, as shown in Fig. 348, one-twelfth actual size. It is a Gramme armature, with single magnetic circuit steel magnets, suspended at or about their centre of gravity by a free suspension and carried on the other end by bearings on the axle. The armature is completely enclosed by casing, and the gear is of steel with teeth cut from the solid, the ratio varying from 3 : 1 to 4·5 : 1.

Heavy Railway Locomotive Motors.—In Plate XX. is given a sketch of the electric locomotive of the City and

South London subway railway, with two 50 H.P. motors designed by Dr. E. Hopkinson and constructed by Messrs. Mather and Platt. Each locomotive weighs about 10 tons, exerts 100 H.P., and can run over 25 miles per hour. They are series-wound, and run with magnets nearly saturated. The tractive effort with 100 amperes is 1180 lbs., with 226 amperes 3000 lbs. Fourteen of these locomotives are now running, and also two others by Siemens of a pattern in which the field-magnets are relatively more powerful, enabling the armature to give the requisite torque with less current. All the fourteen locomotives supplied by Mather and Platt are still at work, having been in service since 1890, and having each run during that time on an average 120,000 miles. The principle of constructing the armature directly on the axle, which Dr. Hopkinson introduced for the first time on this line, has been followed in all cases where large powers at comparatively high speeds have been required, on account of its simplicity, efficiency and the small amount of wear and

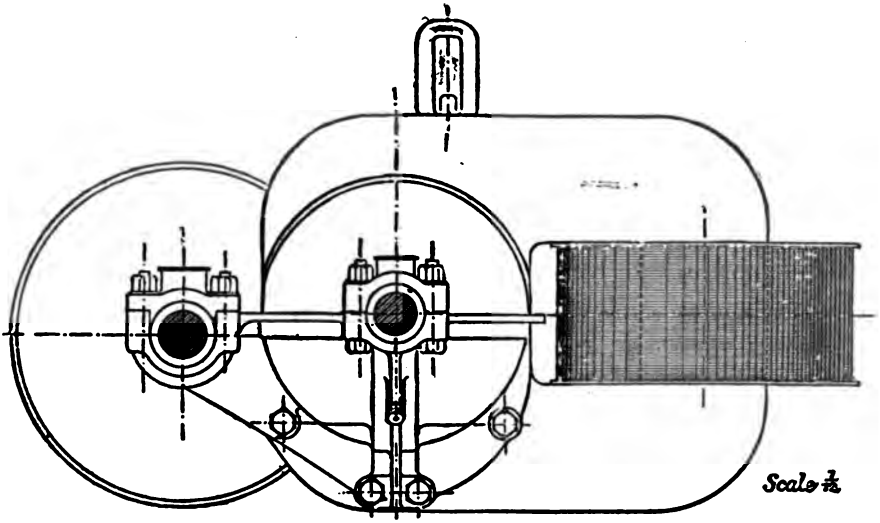

FIG. 348.—MATHER AND PLATT'S SINGLE-REDUCTION MOTOR.

tear. A smaller example is afforded by the 20 H.P. motor used in the Bessbrook Tramway, described by Dr. Hopkinson,[1] which ran at 1000 revolutions per minute, taking 100 amperes at 220 volts. It was series-wound, the resistance of armature being 0·112 ohm, and of magnet 0·113 ohm. The nett efficiency was over 90 per cent. This motor is reversed by simply reversing current in the armature.[2]

A still larger example of solid railway work is afforded by the Liverpool Overhead Railway,[3] the electrical machinery of which was built by the Electric Construction Corporation.

The largest electric locomotives yet made[4] are those designed by the General Electric Company of Schenectady, for the Baltimore and Ohio Railroad. Each locomotive weighs 95 tons, and has on it four motors each of 400 H.P. They are operated at 600 volts, and exert their maximum pull of 47,500 lbs. when running at 15 miles per hour, the current then being 2700 amperes. The motors, of the 6-pole type, are grouped two in series. The generating station will contain four 10-pole 500 kilowatt direct-driven dynamos over-compounded from 600 to 700 volts.

Pulsating motors.—The early type adopted by Page, Hjorth and others, with a reciprocating movement, has been revived in recent years for motors for the special purposes of operating hammers or drills. In 1879, Werner von Siemens[5] produced a mining drill in which a continuous current and an alternating current of slow period were combined to produce a reciprocating movement without a commutator. In 1880 Marcel Deprez[6] designed an electric hammer for forging, having a plunger of iron to be drawn up and down in a cylindrical coil wound in sections, into which the current was successively led by a commutator. Atkinson has lately designed a pulsating motor of remarkable novelty for mining drills.

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[1] *Proc. Inst. Civil Engineers*, xci, part i., 1887–8.

[2] For a full description, see *Railway World*, August 1893.

[3] See paper by J. H. Greathead, before *Iron and Steel Institute, Liverpool*, Sept. 20, 1892. See also *Elec. Review*, xxxii. 151.

[4] See *Engineering*, July 19, 1895.

[5] D.R. Patent, No. 9469 of 1879 (see vol. ii. 389 of Siemens' *Arbeiten*).

[6] *La Lumière Électrique*, ix. 44, 1883.

CHAPTER XXII.

THE PRINCIPLES OF ALTERNATE CURRENTS.

In alternate-current working the current is rapidly reversed, rising and falling in a succession of pulses or waves. Electricity is in fact oscillating backwards and forwards through the line with enormous rapidity, under the influence of a rapidly-reversing electromotive-force. The adjectives *alternate*, *oscillatory*, *periodic undulatory*, and *harmonic* have all been used to describe such currents. The author would prefer the term *wave-currents* as being both shorter and more apposite. The properties of alternate currents differ somewhat from those of continuous currents. They are affected not only by the resistance of the circuit but also by the magnetic reaction commonly called self-induction or inductance; the inductance of the circuit having a choking effect on the alternating currents, diminishing the amplitude of the waves, retarding their phase and smoothing down their ripples. They are also affected by the capacity or condenser action of the circuit. If a condenser is placed in an electric circuit, it completely blocks the flow for continuous currents; but alternating currents can oscillate into and out of its electrodes as though the condenser allowed them to pass through. On account of these peculiarities some preliminary account of alternating currents is needed.

If a coil of suitable form is placed, as in Fig. 350, between the poles of a magnet, and spun around a longitudinal axis, it will have currents generated in it which at each semi-revolution die away and then reverse. In the figure the coil of wire is supposed to be so spun that the upper portion comes towards the observer. In that case, the arrows show the direction of the induced currents delivered to the circuit through the agency of two contact rings (or slip-rings) connected respectively to the ends of the coil. In the position shown, the current will be delivered to the left-hand ring, and returns from the circuit to the right-hand ring; but half a turn later it will be flowing to the right-hand ring and returning from the circuit back to the left-hand ring. Fig. 350 is, in fact, a primitive form of alternator, generating a simple periodically reversed or alternating current; and is, in fact, the kind of alternator known as a "magneto-ringer," used for bell service in telephone sets. The simple revolving coil, by cutting the lines of the magnetic field, sets up periodic electromotive-forces, which change at every half-turn, giving rise to alternate currents. In each whole revolution there will be an electromotive-force, which rises to a maximum and then dies away, followed immediately by a reversed electromotive-force, which also grows to a maximum and then dies away. The wave-form depicted in Fig. 351 serves to illustrate this. The heights of the

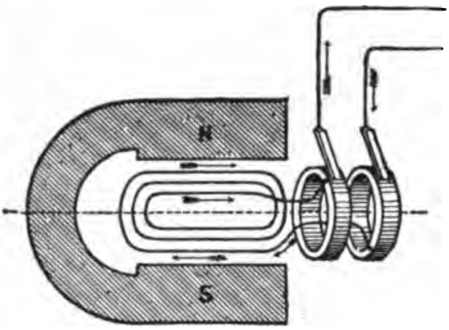

FIG. 850.

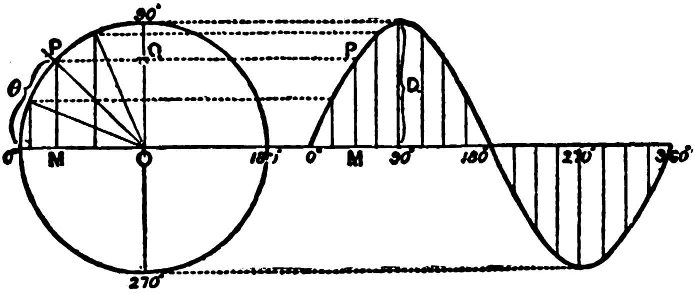

FIG. 351.

curve above the horizontal line represent the momentary values of the electromotive-forces; the depths below, in the second half of the curve, represent the inverse electromotive-forces that succeed them. Each such complete set of operations is called a *period*, and the number of periods accomplished in a second is called the *frequency* or *periodicity* of the alternations, and is symbolized by the letter n. In 2-pole machines n is the same as the number of revolutions per second; but in multipolar machines n is greater, in proportion to the number of pairs of poles. Thus, in an 8-pole field with four north poles and four south poles around a centre there will be produced four complete periods in one revolution, If the machine revolves 15 times a second (or 900 times a minute) there will be 60 periods a second, or the periodicity will be 60. By revolving in a uniform field the electromotive forces set up are proportional to the sine of the angle through which the coil has turned from the position in which it lay across the field. If in this position the flux of magnetic lines through it were N, and the number of spirals in the coil that enclose the N lines be called S, then, as was shown on p. 173, the value of the induced electromotive-force at any time t when the coil has turned[1] through angle $\theta = 2\pi n t$ will be

$$E_\theta = 2\pi n \, S \, \mathsf{N} \sin\theta \div 10^8,$$

or, writing D for $2\pi n \, S \, \mathsf{N} / 10^8$, we have

$$E_\theta = D \sin\theta.$$

In actual machines the magnetic fields are not uniform, nor the coils simple loops, so the periodic rise and fall of the electromotive-forces will not necessarily follow a simple sine law. The form of the impressed waves will depend on the shape of the polar faces, and on the form and breadth of the coils. But in most cases we are sufficiently justified in assuming that the impressed electromotive-force follows a sine law, so that the value at any instant may be expressed in the above form, where D is the maximum value or *amplitude* attained by E, and θ an angle of *phase* upon an imaginary circle of reference. As diagrams of lines revolving around a centre are much used in explaining alternate-current actions, the following explanation [1] should be most carefully followed. Consider a point P revolving clockwise round a circle (Fig. 351). If the radius of this circle be taken as unity, P M will be the sine of the angle θ, as measured from 0°. Let the circle be divided into any number of equal angles, and let the sines be drawn similarly from each. Then let these sines be plotted out at equal distances apart along the horizontal line, as in Fig. 351, giving us the sine curve.

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[1] If n is the number of revolutions per second, $2\pi n$ will be the total angle (in radians) turned through in one second. Hence, the angle turned through (which we call θ), in any short time t will be equal to t times $2\pi n$. For example, if $n = 15$, $2\pi n = 94{\cdot}2$ radians per second, and during, say one-eightieth of 1 second, the angle passed over will be 1·18 radians, or about 67°.

Now, the use that we make of this diagram is this. We know that as time goes on, the value of the electromotive-force is changing from instant to instant. To find its value at any particular instant, we *treat time as if it were an ever-increasing angle;* we take the number of seconds or the fraction of a second, that has elapsed since a certain instant t_0 (when the electromotive force was zero), and multiply it by $2 \pi n$, then considering this as an angle expressed in radians, the sine of this angle multiplied by D gives us in volts the electromotive-force for the particular instant. It will therefore be seen that the point P, in revolving uniformly round the circle in Fig. 351, represents the lapse of time. If we consider it revolving at such a speed that it passes through $2 \pi n$ radians in one second, then the perpendicular P M represents (to some scale or other) the electromotive-force at any particular instant. Now taking the horizontal line 0°–360° to represent time (to some convenient scale), it is evident that after the lapse of the time measured by the distance from 0° to M the electromotive-force has the value M P; and in the same way, at any other instant, the electromotive-force is represented by the perpendicular drawn from that point in the line which represents the instant to the sine curve shown in the figure. In Fig. 351, one revolution of P around the circle of reference corresponds to one complete alternation or cycle of changes. The value of the electromotive-force (which varies between + D and – D as its maximum values) may be represented at any moment either by the sine P M or by projecting P on to the vertical diameter, giving O Q. As P revolves, the point Q will oscillate along the diameter. We may, therefore, without drawing our sine curve at all, merely consider a line O P (drawn to some scale to represent D) as revolving round O, and take its projection O Q at any instant as the electromotive-force. Such a diagram is known as a *clock diagram.*

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[1] Those who are not familiar with the problems of simple-harmonic motions should consult some modern treatise of theoretical mechanics on the subject.

The currents which result from these periodic or alternating electromotive-forces are also periodic and alternating; they increase to a maximum, then die away and reverse in direction, increase, die away, and then reverse back again. If the electromotive-force completes 100 such cycles or reversals in a second, so also will the current.

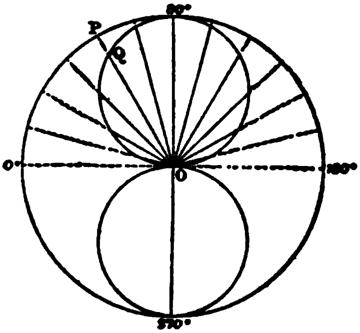

Fig. 352.

There is yet another way of representing periodic variations of this kind—namely, by a diagram akin to that used by Zeuner for valve-gears. Let the outer circle (Fig. 352) be as before a circle of reference around which P revolves. Upon each of the vertical radii describe a circle. Then the lengths such as O Q, cut off from the radii, represent the corresponding values of the sine of the angle. If a card with a narrow slit cut radially in it were made to revolve over this figure, the intersection with the two inner circles would show the varying electromotive-forces in various positions.

The reader who desires to pursue the graphic study of these matters further should consult the excellent treatise of Prof. Fleming,[1] or that of Mr. Blakesley,[2] and sundry papers by Mr. Kapp.[3] Bedell and Crehore,[4] devote a whole chapter to the subject. In the case of real machines in which the magnetic fields are not uniform, nor the coils simple loops, the periodic rise and fall of the electromotive-forces will not necessarily follow a simple sine law. The form of the impressed waves will depend upon the shape of the polar faces, and on the form and breadth of the coils. Consider the case, of a machine in which the field-magnets consist of a double crown of opposing poles (as in the machines of Siemens, Ferranti, Mordey, etc.). If the armature coils and magnet cores are both of circular form, and equal in diameter, as the coils approach the polar ends of the cores they will,.it is true, gradually enter the field, and the number of lines cut by the coil during equal displacements will gradually increase and become a maximum when the axis of coil and core coincides, and from that point it will again decrease, almost in a sine law; the greatest rate of cutting being when the edge of the coil is opposite the centre of the core; but if coil and core be rectangular in outline, the greatest rate of cutting in each wire will be when one edge of the coil is passing the edge of the pole. In this case the sine law cannot be true for the electromotive force. In order to test whether in any given dynamo the rise and fall of electromotive-force and of current in the armature coils conforms to the law of sines, experiments are necessary. Joubert, in order to measure the currents of a Siemens dynamo, employed an electrometer method, and took off the current at any desired phase by a special commutator, and found an approximate curve of sines.[5] Another method, applicable also to direct-current machines, due to Mr. Mordey, is described.

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[1] Fleming, *The Alternate Current Transformer*, London, 1889. Also a paper on Polar Diagrams, *Electrician*, xxxv. 48.

[2] Blakesley, *Alternating Currents of Electricity*, London, 1889.

[3] Kapp on "Alternate Current Machinery," *Proc. Inst. Civil Engineers*, 1889, pt. iii.

[4] Bedell and Crehore, *Alternating Currents*, London, 1893.

[5] For references as to modern varieties of this method see p. 712. During recent years many experimental methods have been given for determining the shape of the curve followed by the variations of alternating electromotive-forces and currents. The reader should consult the methods pursued by Ryan,

In Fig. 353 are given four curves for a half-period. Of these one is a sine-curve, the other three from actual alternators, showing how nearly they agree with a true sine-curve. The one which agrees most nearly is that of the Mordey alternator, which lies just within the sine-curve nearly throughout its whole extent. The curve is usually more peaked in machines which have the coils sunk between iron teeth and have much armature-reaction. In the Niagara generators they are, on the contrary, rather flatter-topped and broader than true sine-curves. We are then sufficiently justified in assuming that the impressed electromotive-force follows a sine law.

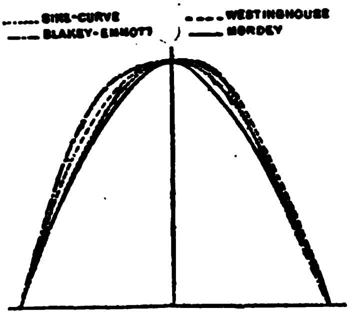

FIG. 353.—CURVES OF ALTERNATORS.

"*Virtual*" *Volts and Amperes.*—Alternate current voltmeters and alternate-current amperemeters do not measure

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Amer. Inst. Elec. Engineers, 1888 and 1889; also *Electrician*, xxiv. 263, 1890; Bedell, Miller and Wagner, *Amer. Inst. Elec. Engineers*, x. p. 500; Fleming, *Electrician*, xxxiv. 460, 507, 1895; L. Duncan, *ibid.* 617; Hicks, *ibid.* 698. Fleming's method is applicable to determine the form of the current curve at any part of a circuit. See also a paper by Barr, Burnie and Rodgers, *Electrician*, xxxv. 719.

Some controversy arose in the columns of the *Electrician* and of the *Electrical World*, in the autumn of 1894, as to whether there was any advantage in alternators giving a sine-curve. Fleming has since found that certain transformers worked with a distinctly higher efficiency when operated by an alternator giving a peaked curve than when operated by one giving a nearly pure sine-curve for the electromotive-force. On the other hand, this form appears to be undesirable for motor-running. As a matter of fact, the form of the current curve depends, not only on the construction of the alternator, but also upon the modifying influences of capacity and self-induction in the circuit. The presence, in the circuit, of transformers with iron cores and of motors will modify the curve; and the modification will specially depend on the degree of saturation to which the iron cores are carried at each cycle. A paper by Barr, Beeton and Taylor, in the *Electrician*, xxxv. 257, 286, is of great importance.

the arithmetical average values of the volts and of the amperes. They measure what are called *virtual volts* and *virtual amperes.* In a Cardew voltmeter the heating of the wire depends on the square of the current. In an electro-dynamometer the torque depends at every instant on the product of the currents in the fixed and movable parts; therefore, when used as an amperemeter, depends on the square of the current. The attraction (or repulsion) in electrostatic voltmeters is proportional to the square of the volts. The readings which these instruments give us, if first calibrated by using steady currents, are not true means, but are the square roots of the means of the squares. Now the mean[1] of the squares of the sine (taken over either one quadrant or a whole circle) is $\frac{1}{2}$; hence the square-root-of-mean-square value of the sine functions is got by multiplying their maximum value by $1 \div \sqrt{2}$, or by 0·707. But[2] the arithmetical mean of the values of the sine is 0·637. Hence an alternating current, if it obey the sine law, will produce a heating effect greater than that of a steady current of the same average strength, by the ratio of 0·707 to 0·637; *i. e.* about 1·1 times greater. If a Cardew voltmeter is placed on an alternating circuit in which the volts are oscillating between maxima of + 100 and - 100 volts, it will read 70·7 volts, though the arithmetical mean is really only 63·7; and 70·7 steady volts would be required to produce an equal reading.

The term *virtual*[3] has been used to denote these square-

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[1] See proof, p. 558.

[2] Or more strictly

$$\frac{1}{\theta}\int_0^\theta \sin\theta\, d\theta = \frac{1-\cos\theta}{\theta},$$

whence, if $\theta = \frac{\pi}{2}$, the average is $\frac{2}{\pi}$,

[3] I adhere to the term *virtual*, which was in use before the term *efficace* which was recommended in 1889 by the Paris Congress to denote the square-root-of-mean-square value. I adhere to it mainly because the adjective *effective* is required in its usual meaning in kinematics to represent the resolved part of a force which acts obliquely to the line of motion, the effective force being the whole force multiplied by the cosine of the angle at which it acts with respect to the direction of motion.

root-of-mean-square values. If an alternate-current amperemeter reads 100 amperes, that means that the current really rises to + 141·4 amperes and then reverses to – 141·4 amperes; but the heating effect and the amount of power delivered are the same as if the current were 100 continuous amperes, and therefore such a current would be described as 100 virtual amperes.

It may be remarked in passing that the virtual electromotive-force of a dynamo wound for alternate currents will therefore be 1·1 times higher (compare p. 589) than that of the same dynamo wound as a continuous-current dynamo of the same current-carrying capacity; or will be 2·2 times higher if, while the same wire is used, the alternator is not re-entrant, but forms a single circuit.

The distinction between virtual and maximum values is important since certain effects—for example the tendency to pierce insulation with a spark—depend on maximum, not on virtual values. For example, if an electrostatic voltmeter reads 10,000 volts; the maximum value (supposing the law of variation a sine law) will be 14,142 volts. If the curve is more peaked than that of the sine curve, the maximum will be higher.

Use of Clock Diagrams.—In these polar diagrams the amperes or the volts that are undergoing periodic cycles of change are represented by the projection on some given line (in this book, the projection on a vertical line is taken) of a line supposed to revolve about a centre. Such diagrams are of so frequent use in the study of alternating currents that a few further points about them are given.

Differences of *phase* are in the clock diagram represented by differences of angular position. For example, if two revolving pointers O V and O C (Fig. 354) are going round at the same rate, but always one a little behind the other, they will not come to their respective maximum at the same instant. Projecting them upon the vertical line we see that at the moment when O V has revolved so far that the angle of position is θ, its projection will have the value O v; while the other pointer, which lags behind by an amount measured by the angle ϕ (=V O C), has for its value as projected, the length O c. When O v gets to its maximum (that is when V arrives at the top), O c will still be behindhand. The values of the two projections are $O\,v = O\,V \,.\, \sin \theta$; and $O\,c = O\,C \,.\, \sin (\theta - \phi)$. The angle ϕ is the *difference of phase.*

To add together two different alternating quantities—for instance two electromotive-forces—that have the same period, it is not sufficient simply to add their numerical values. For instance, if there are two coils in series in a circuit in one of which there is being induced an alternating electromotive-force of 40 volts, and in the other an alternating electromotive-force of 30 volts (both having, let us say, the same frequency of 100 periods per second), the total electromotive-force will not be 70 volts unless the two electromotive-forces happen to be exactly "in phase." If there is any difference of phase between them the resultant will be less than 70 because they do not come to their maxima at the same time. To ascertain the value they have when added together we must apply the principle of summation of vectors with which every engineer is familiar in the ordinary compounding of forces by constructing a parallelogram.

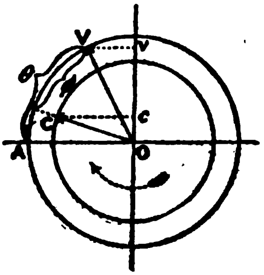

FIG. 854.

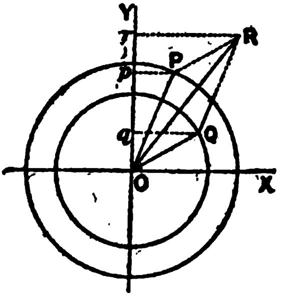

FIG. 855.

Let O P and O Q represent two electromotive-forces, of the same period, but with a phase difference between them of P O Q which we may call angle ϕ. Completing the parallelogram by drawing P R equal and parallel to O Q, we get the resultant O R which represents the relative magnitude and phase of the resultant revolving vector. The projection O r of this line will always be equal to the sums of the projections O p and O q of the two components. Now, by ordinary geometry we have $\text{O R} = \sqrt{\text{O P}^2 + \text{O Q}^2 + 2 \text{ P Q} \cos \phi}$. This is obviously a maximum when ϕ = zero. For instance if in the above example O P = 40, O Q = 30, and ϕ = 37°. it will be found that the resultant O R is 66·6.

If the two components are at right angles to one another, on the diagram one will have its maximum at the instant when the other has its minimum. They are then said to be *in quadrature*, or as some electricians say, in *quarter-phase*. If they are equal in themselves the resultant will be greater than them in the proportion $\sqrt{2}$ to 1. For example, the resultant of two alternating electromotive-forces of equal period, of 100 (virtual) volts each, that are in quadrature, is 141·4 (virtual) volts.

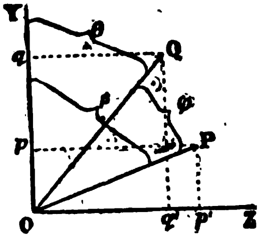

Fig. 356.

Products of Periodic Functions.—Suppose we have two periodic functions—say two currents, or a current and an electromotive-force — both varying with the same periodicity, but having different amplitudes and a difference of phase between them. Let one be called $p = \text{O P} \sin \theta$; the other $q = \text{O Q} \sin \beta$; where O P and O Q are their respective maximum values (as in Fig. 356), and ϕ the angle of phase-difference between them equal to $\theta - \beta$. Now, suppose we want to find the mean value of the product $p\ q$. This product will itself vary, but not as a sine function, and therefore is incapable of being represented as a line revolving.. It will at certain instants—four times in each cycle—have zero values, for p comes twice to zero, and q comes also twice to zero. It will also have negative values when either p or q is negative. Its mean value will be the mean of all the values of the product during one complete cycle.

At the instant shown the product will be $p\ q = \text{O P} \,.\, \text{OQ} \cos \theta \,.\, \cos \beta$. A quarter-period later the two lines O P and

O Q will stand to the axis — O Y in the same relations as they now stand to the axis O X, and the product (being positive) will then be

$$p' q' = \mathrm{O\,P} \,.\, \mathrm{O\,Q} \sin\theta \,.\, \sin\beta.$$

Taking the mean of these two values, we have

$$\begin{aligned} \frac{pq+p'q'}{2} &= \tfrac{1}{2}\,\mathrm{O\,P} \,.\, \mathrm{O\,Q}\,(\cos\theta \,.\, \cos\beta + \sin\theta \,.\, \sin\beta) \\ &= \tfrac{1}{2}\,\mathrm{O\,P} \,.\, \mathrm{O\,Q} \cos(\theta-\beta) \\ &= \tfrac{1}{2}\,\mathrm{O\,P} \,.\, \mathrm{O\,Q} \cos\phi. \end{aligned}$$

Now this is obviously independent of the actual position of θ or of β; that is to say, for every position the mean of the value between that position and the position at right angles is the same all the way round. Hence this value is the required true mean value of the product.

We shall make use of this theorem later.

A geometrical construction to illustrate the above is given in Fig. 357. Let O P and O Q represent the maximum values of two periodic functions as having phase-difference the angle ϕ or P O Q. Turn either of them (in this case O P) through a right angle so that it occupies the position O S, then complete the parallelogram O Q T S, and draw the triangle O Q S. The area of the parallelogram is equal to O P . O Q cos ϕ, and the area of the triangle is equal to $\frac{1}{2}$ O P.O Q cos ϕ, and therefore represents the mean product.

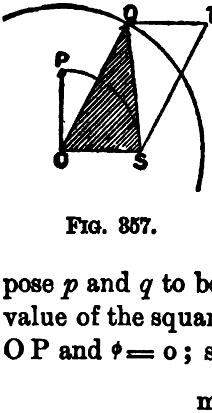

FIG. 357.

A further deduction is of use. Suppose p and q to be identical; we shall then obtain the mean value of the square of the periodic function by writing O Q = O P and $\phi = 0$; so that cos $\phi = 1$. Then we get,

$$\text{mean value of } p^2 = \tfrac{1}{2}\,\mathrm{O\,P}^2.$$

In other words, the mean value of the square of the sine is $\frac{1}{2}$.

Lag and Lead.—Alternating currents do not always keep in step with the alternating volts impressed upon the circuit. If there is inductance in the circuit the currents will *lag;* if there is capacity in the circuit they will *lead* in phase. Fig. 358, illustrates the lag produced by inductance. The curve marked V represents the alternating volts; that marked C is the current curve. Distances measured from O along the horizontal line represent time. These curves are in fact similar to what would be obtained if curves were plotted from Fig. 354 in the same way as that plotted in Fig. 351, the points V and C being taken instead of the point P. The impulses of current, represented by the blacker line, occur a little *later* than those of the volts. But inductance has another effect of more importance than any retardation of phase; it produces reactions on the electromotive-force, choking the current down. While the current is increasing in strength the reactive effect of inductance tends to prevent it rising. To produce a current of 40 amperes in a resistance of 1½ ohms would require—for continuous currents—an E. M. F. of 60 volts. But an alternating voltage of 60 volts will not be enough if there is inductance in the circuit reacting against the voltage. The matter is complicated by the circumstance that the reactive impulses of electromotive-force are also out of step: they are, in fact, exactly a quarter period behind the current.

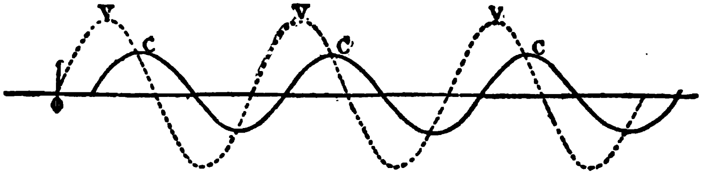

FIG. 358.—CURVE OF CURRENT LAGGING BEHIND CURVE OF VOLTS.

The Reaction of Inductance.—We have seen that every current is surrounded with a whirl of magnetic lines all along its length, the number depending on the permeability of the medium, and the distance between the going and returning wires. If the circuit consists of coils whose convolutions lie near one another, the whirls or loops of magnetic lines belonging to one part of the circuit will enclose another part of the circuit; so that whenever the current is growing or dying away these loops of magnetic lines will be cutting across some other part of the circuit. In fact there will be *self-induction*, and the amount of cutting of magnetic lines that goes on when unit current is turned on or off (and which we may call the coefficient of self-induction, symbol L) will be proportional to the square of the number of spirals so reacting; or L is proportional to S^2. The presence of an iron core helps the magnetic field due to each convolution to thread itself around all the other convolutions. If the sectional area, length and permeability of the magnetic circuit in question are A, l and μ; then $L = 4 \pi S^2 \mu \div 10^9 l$; where the factor 10^9 is introduced because the unit of induction, the *henry*, is chosen to correspond to the ohm and other units.

So then whenever in a circuit having an inductance L, the current is growing, there will be a self-induced electromotive-force reacting and tending to prevent the current growing; and the magnitude of this will be proportional both to L and to the rate of change of the current. If an alternate current of C (virtual) amperes is flowing with a frequency of n cycles per second through a circuit of inductance L, the reactive electromotive-force,[1] will be $2 \pi n$ L C (virtual) volts. If, for example, $L = 0{\cdot}002$ henry, $n = 50$ periods per second, and $C = 40$ amperes, the reactive electromotive-force will be 25·1 volts. Now, if we wish to drive the 40 (virtual) amperes not only through the resistance of 1½ ohms but against this reaction, we shall require more than 60 volts. But we shall not require 60 + 25·1 volts, since the reaction is out of step with the current. Ohm's law is no longer adequate by itself as a guide. To find out what volts will be needed we must calculate, either by algebra, or by geometry; and for greater simplicity we will have recourse to geometry.

---

[1] This is calculated as follows. By definition, L, the coefficient of self-induction, or inductance, represents the amount of self-enclosing of magnetic lines by the circuit when the current has unit value; when current has value C the number of lines enclosed is C times L. And, as the self-induced electromotive-force is proportional to the rate of change of this number, we may write $E = L.\ d\,C\,/\,d\,t$. Now C is assumed to be a sine function of the time having instantaneous value $C_0 \sin. 2 \pi n t$; where C_0 is the maximum value of C. Differentiating this with respect to time we get $d\,C\,/\,d\,t = 2 \pi n\, C_0 \cos 2 \pi n t$. The "virtual" values of cosine and sine being equal we have for E the value $2 \pi n$ L C, but differing in phase from the current by a ¼ period.

Geometrical Investigation of the Law of Alternate Currents.—Plot out (Fig. 359) the wave-form O A *b* *d*, to correspond to the volts necessary to drive the current through the resistance, if there were no inductance. The ordinate *a* A may be taken to scale as 60. This we may call the R C curve. Then plot out the curve marked —*p* L C to represent the volts needed to balance the reaction of the inductance. Here *p* is written for 2 *π* *n*. The ordinate at O is 25·1: and

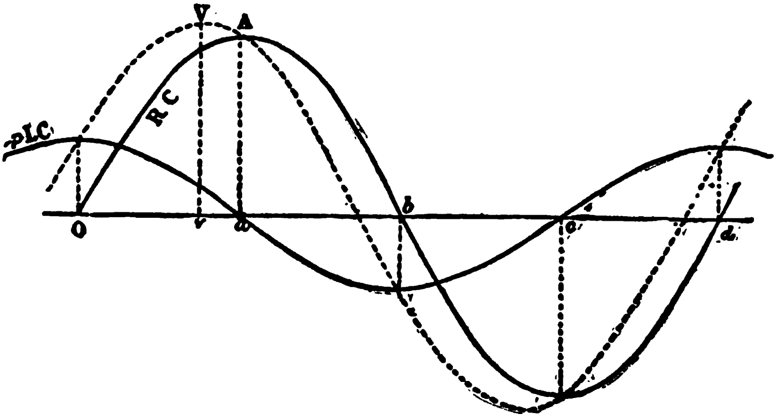

FIG. 359.

the curve is shifted back one-quarter of the period: for when the current is increasing at its greatest rate, as at O, the self-inductive action is greatest. Then compound these two curves by adding their ordinates, and we get the dotted curve, with its maximum at V. This is the curve of the volts that must be impressed on the circuit in order to produce the current. It will be seen that the current curve attains its maximum a little after the voltage curve. The current lags in phase behind the volts. If O *d* is the time of one complete period the length *v* *a* will represent the time that elapses between the maxima of volts and amperes. In Fig. 360 the same facts are represented in a revolving diagram of the same sort as

Fig. 354. The line O A represents the working volts R × C, whilst the line A D at right angles to O A represents the self-induced volts p L C. Compounding these as by the triangle of forces, we have as the impressed volts the line O D. The projections of these three lines on a vertical line while the diagram revolves around the centre O give the instantaneous values of the three quantities. The angle A O D, or ϕ, by which the current lags behind the impressed volts, is termed the *angle of lag*. However great the inductance or the frequency, angle ϕ can never be greater than 90°. If O A is 60 and A D is 25·1, O D. will be 65 volts. In symbols, the impressed volts will have to be such that $E^2 = (R\ C)^2 \times (p\ L\ C)^2$. This gives us the equation :

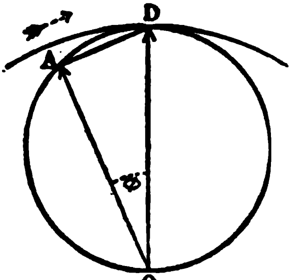

FIG. 360.

$$C = \frac{E}{\sqrt{R^2 + p^2 L^2}} \quad . \quad . \quad . \quad . \quad . \quad [I.]$$

The denominator which comes in here is commonly called[1] *the impedance*. Comparing this with the law for continuous currents, namely

$$C = \frac{E}{R},$$

we see that the effect of the inductance is to make the circuit act as if its resistance, instead of being R, was increased to $\sqrt{R^2 + p^2 L^2}$. In fact the alternate current is governed, not by the resistance of the circuit, but by its impedance. The equation tells us the *magnitude* of the current, but not its *phase*.

---

[1] The term *impedance* strictly means the ratio of any impressed electro-motive-force to the current which it produces in a conductor (see Lodge's *Modern Views*, p. 398), of which the above is only one case. For steady currents the impedance is simply the resistance. For variable currents it may be made up of resistance, of inductance, and (if the circuit has electrostatic capacity), of permittance, in various proportions according to the *form* of the variation. For true periodic currents obeying the sine-law the impedance is the square root of the sum of the squares of resistance and inductance. For currents which vary more suddenly the impedance will depend more on self-induction and less on resistance.

In Figs. 361 and 362 the angle of lag is seen to be such that $\tan\phi = p\,L\,C / R\,C$ or $= q\,L / R$. The current is lagging as if the angle of reference were not θ but $\theta - \phi$, so that the equation for C_t the instantaneous value of C at the moment when $E = D \sin\theta$, is

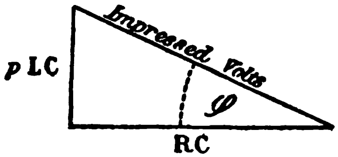

FIG. 361.

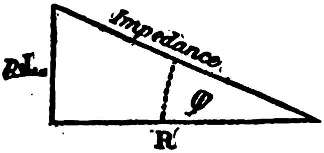

FIG. 362.

$$\frac{D\sin(\theta - \phi)}{\sqrt{R^2 + p^2 L^2}} \quad . \quad . \quad . \quad . \quad . \quad . \qquad [\text{II.}]$$

This is Maxwell's law[1] for periodic currents as retarded by inductance. As amperemeters and voltmeters take no account of phase but give virtual values, the simpler form preceding is usually sufficient.

The relation between resistance and impedance is readily got from the triangle in Fig. 362; for clearly the angle ϕ is such that

$$\sin\phi = \frac{p\,L}{\sqrt{R^2 + p^2 L^2}}$$

$$\cos\phi = \frac{R}{\sqrt{R^2 + p^2 L^2}},$$

$$\tan\phi = \frac{p\,L}{R}.$$

If we prefer we may substitute for the impedance in the denominators of the preceding equations its value $R / \cos\phi$.

The equations established above hold good, whether maximum or virtual values are used. For example, we may write

---

[1] The analytical proof is given at the end of the present Chapter, p. 578.

$$\text{Maximum C} = \frac{\text{maximum E}}{\text{impedance}};$$

or

$$\text{Maximum C} = \frac{\text{maximum E}}{\text{resistance}} \times \cos \phi;$$

and

$$\text{Virtual C} = \frac{\text{virtual E}}{\text{impedance}};$$

or

$$\text{Virtual C} = \frac{\text{virtual E}}{\text{resistance}} \times \cos \phi.$$

The clock diagrams of revolving lines may be drawn either with maximum or virtual values.

Effect of capacity.—When an electromotive-force is applied to a condenser the current plays in and out, charging the condenser in alternate directions. As the current runs in at one side and out at the other, the dielectric becomes charged, and tries to discharge itself by setting up an opposing electromotive-force. Its opposing potential rises just as its charge increases. A mechanical analogue is afforded by the bending of a spring, which as it is being bent exerts a back-force proportional to the amount of bending to which it has been subjected. When a periodic force is applied to a spring the elasticity of the spring tends to hasten the return movement. In like manner the electric elasticity of a condenser tends to hasten the return flow of the current.

The effect of capacity introduced into an alternate current circuit is to produce a *lead* in the phase of the current, since the reaction of a condenser, instead of tending to prolong the current, tends to drive it back. The student must clearly distinguish between the case of capacity in series with a circuit and the case of capacity in parallel with a branch of a circuit. What is said here refers to capacity in series, that is to say, the conductor of the circuit is actually cut and the ends joined to a condenser so that no current can flow except into and out of the condenser. If the capacity is in parallel with a branch of a circuit, and we are considering what happens in that branch when there is a *given* alternating pressure at its ends, the capacity in parallel has no effect at all. If we are only given the pressure at some other part of the circuit, then the problem becomes more complex and involves the impedances of the circuit's various branches. Returning then to a simple circuit with a condenser in series, the smaller the capacity of the condenser the more does it react. The reactance is therefore written as $-1/pK$, being negative and inversely proportional to K (the capacity in *farads*) and to p; and the angle ϕ will be such that $\phi = -1/pKR$. The impedance will be $\sqrt{R^2 + 1/pK^2}$. Figs. 363 and 364 show the construction that is applicable in this case.

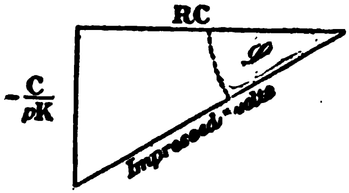

FIG. 363.

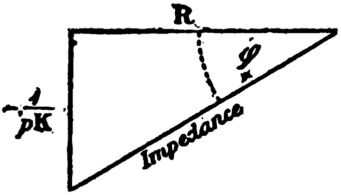

FIG. 364.

If both inductance and capacity are present, $\tan\phi = (pL - 1/pK)/R$; the reactance will be $pL - 1/pK$; and the impedance $\sqrt{R^2 + (pL - 1/pK)^2}$. This is illustrated by Fig. 365, in which the triangle for finding ϕ is drawn by setting out p L at right angles to R and then deducting from p L a part equal to $1/pK$.

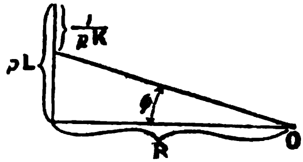

FIG. 365.

The same construction may be applied to a circuit containing several resistances, inductances and capacities.

Since capacity and inductance produce opposite effects, they can be used to neutralize one another. They exactly balance if $L = 1/p^2K$. In that case the circuit is non-inductive and the currents simply obey Ohm's law.

It will be seen that if in a circuit there is little resistance and much reactance, the current will depend almost exclusively on the reactance. For example, if p ($= 2\pi n$) were, say, 1000 and $L = 10$ henries, while R was only 1 ohm, the resistance part of the impedance would be negligible, and the law would become

$$C = \frac{E}{pL}.$$

The current would *lag* by almost 90°.

Self-induction coils with large inductance and small resistance are sometimes used to impede alternate currents, and are called *choking coils*, or impedance coils. This formula is wanted for calculating alternate-current electromagnets; for their apparent resistance is almost entirely due to inductance.

If the current were led into a condenser of small capacity (say $K = \frac{1}{10}$ microfarad, then $1 / pK = 10{,}000$), the current running in and out of the condenser would be governed only by the capacity and frequency, and not by the resistance, and would have the value—

$$C = EpK,$$

and its phase will *lead* by almost exactly 90°.

A capacity acting laterally across the circuit, as when a condenser is placed across the two mains, has the effect of increasing the flow of current from the dynamo up to the points on the circuit which are connected to it, and therefore of raising the virtual potentials of those points, thereby affecting the voltage of the rest of the circuit. There is, for a given frequency, resistance and self-induction, one particular value of capacity which would enormously increase the current and voltage as by a sort of resonance. These various condenser effects have been considered by various writers. A very clear exposition of them, together with the phenomena observed on the Ferranti mains on the Deptford supply has been given by Fleming.[1]

Mean Power.—The power cannot be calculated by simply multiplying together the *volts* and the *amperes* as with continuous currents; for when there is any difference of phase the *apparent watts* so calculated are always in excess of the *true watts*. We have seen on p. 558 that the mean product of two periodic functions is equal to half the product of their maximum values multiplied by the cosine of their phase difference: or

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[1] *Journal Inst. Electr. Engineers*, xx. 362, 1891.

$$\text{Mean power (true watts)} = \tfrac{1}{2}\, E_{\max} \times C_{\max} \times \cos\phi.$$
$$= \frac{E_{\max}}{\sqrt{2}} \times \frac{C_{\max}}{\sqrt{2}} \times \cos\phi,$$
$$= E_{\text{virt}} \times C_{\text{virt}} \times \cos\phi.$$

One way of dealing with this is to consider the product $E_{\text{virt}} \times \cos\phi$ as the resolved part of the volts that is in phase with the current, and therefore equal to $C_{\text{virt}} \times R$. Hence we may write the mean power (true watts) as $C^2_{\text{virt}}\, R$. That is to say, if the resistance of the circuit is a plain non-inductive resistance (such as a load of lamps, or a water resistance) the true watts spent in it are found in the usual way by the $C^2 R$ law. There is, however, another way of regarding the matter as follows.

Watt-less Current.—Whenever there is a great phase difference between volts and current (whether a lag due to self-induction or a lead due to capacity), the true watts are, as has already been pointed out, much less than the apparent value that would be obtained by merely multiplying together the virtual amperes and the virtual volts. For, as we have seen, this product must be further multiplied by the cosine of the angle of lag (or lead). Now there are two ways of looking at this matter, the product $E_{\text{virt}} \times C_{\text{virt}} \times \cos\phi$ may be regarded as either the product of the virtual amperes into the resolved part (or effective part) of the virtual volts, or it may be regarded as the product of the virtual volts into the resolved part of the virtual amperes. Just as any force may be resolved into two component forces at right angles to one another, so any alternating current may be resolved into two component alternating currents differing 90° in phase. Or C may be resolved into two parts, $C \cos\phi$ agreeing in phase with the volts, and $C \sin\phi$ in quadrature with the volts. These two resolved parts of the current may be termed the *working current* and the *watt-less current*. In Fig. 366, O E represents the effective part of the impressed electromotive-force O A. Of O E a part O I is found, by dividing by R (p. 569), to represent the current C. Of this current the resolved part O W, in phase with O A, is the working current, and the part O U, which is in quadrature with O A, is the watt-less current. Whenever, for either cause, the angle of lag is great, the watt-less part of the current will be great also. For example, when transformers are left on open circuit, the current in the primary is nearly in quadrature (owing to self-induction) with the impressed volts, and, if it were not for hysteresis or eddy-currents in the iron cores, would be almost entirely watt-less.

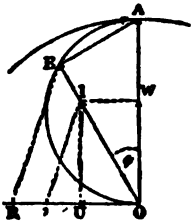


FIG. 866.

For example, if there is a current of 100 virtual amperes lagging 14° behind the impressed volts, this may be resolved into a working current of 97·03 virtual amperes, and a watt-less current of 24·2 virtual amperes.

Measurement of Alternate-current Power.—The considerations above show that this is a matter for care. If there is no phase-difference between volts and amperes, the apparent watts are the same as the true watts; and in that case amperemeter and voltmeter may be used.[1] But if there is a phase difference a suitable wattmeter must be used; the usual form being an electrodynamometer specially constructed so that the high-resistance circuit in it shall be non-inductive.

Numerical Example:—Let an impressed electromotive-force of 65 (virtual) volts, alternating with a frequency of 50 periods per second, act upon a circuit having resistance 1·5 ohms, and a coefficient of self-induction of 0·002 henry. Find the lag, the current, and the mean power.

To find the lag, we must find the inductance, $2 \pi n \mathrm{L}$, and divide this by the resistance; or

$\tan \phi = 2 \pi n \mathrm{L} \div \mathrm{R} = 2 \times 3{\cdot}1416 \times 50 \times 0{\cdot}002 \div 1{\cdot}5 = 0{\cdot}419.$ Looking in a table of natural tangents, we find that ϕ will be 22° 44′; whence a table of natural cosines gives us $\cos \phi = 0{\cdot}9223$.

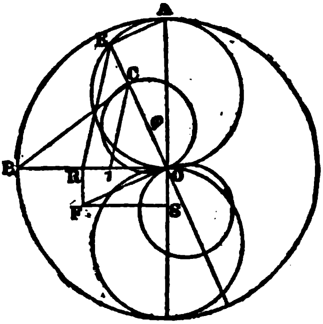
---

[1] Those who are not familiar with this subject should consult the writings of Mr. Blakesley or those of Prof. Fleming. The three-dynamometer method of Blakesley, the three-voltmeter method of Ayrton, and analogous methods, are all of value. Fleming in *Journal Inst. Electr. Engineers*, xxi. 594, 1892, has after much experience given preference to a simple wattmeter method.

Or, we might calculate cos ϕ directly as R ÷ $\sqrt{R^2+4\pi^2 n^2 L^2}$. Multiplying cos ϕ into the 65 volts, we get 59·95, say 60, as the effective virtual volts, and dividing by the resistance gives 40 virtual amperes as the current. The mean power is 65 × 40 × 0·9223 = 2400 watts.

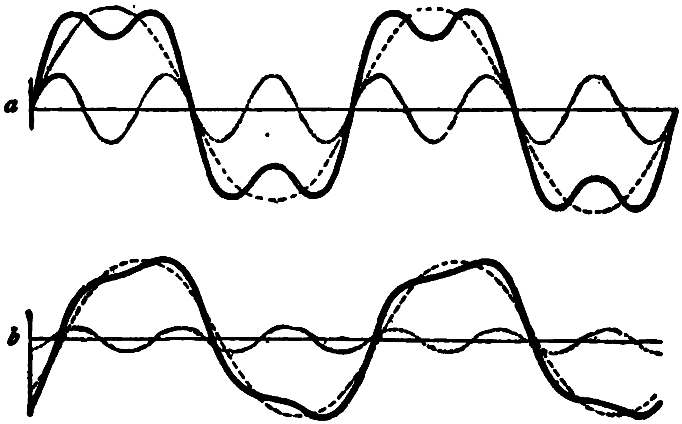
Geometrically this is given in Fig. 367.

Let O A be 65 to any scale, the impressed (virtual) volts. Describe the circle of radius O A, and the semicircle O E A. Draw O B at right angles to O A. On O B set off O R on any convenient scale of resistance, O 1 being taken as 1 ohm. Using same scale, set off O S or R F at right angles, equal to the inductance $2\pi n L = 0{\cdot}628$. Join O F. R O F is the angle of lag. Draw E O at right angles to O F, cutting semicircle in E. E O A is also angle of lag, hence E O represents effective virtual volts; and A E the cross-electromotive-force of self-induction $2\pi n L C$. Join E R and from 1 draw 1 C parallel; C O will represent the current. As O B is O A turned through a right angle, the area of triangle B O C = ½ O A. O C . cos A O C = ½ mean power (see p. 558).



There are some reasons why it is desirable that the induction curves of alternators should follow the sine-form (but see p. 712 as to effect of wave-form on transformer efficiency). According to the well-known theorem of Fourier, every complex single-valued periodic function can be analyzed down into a series of simple periodic functions differing in amplitude and phase, but all belonging to a harmonic series, having frequencies that are some exact multiple of a single fundamental frequency. Every complex wave-curve may be regarded as built up of sine-curves. For example, the curve shown in Fig. 368 may be looked upon as a compound of the two dotted sine-curves, one of a frequency three times that of the other. Now, if this complex curve represents the impressed electromotive-force of an alternator with curiously-shaped poles, what will the curve of effective electromotive-force (or of current) be when self-induction is present? The amplitude is cut down in proportion nearly to the frequency of the alternation. Hence the component ripple, which has three times the frequency, will be damped out nearly three times as much as the fundamental wave.[1] In Fig. 369 are shown the two waves, as altered by a lag of 41° which cuts down the fundamental to 0·75, and the ripple to 0·35 of their respective amplitudes; the resultant wave being also shown. It is evident that self-induction tends to smooth out the ripples, including all parts of the wave that do not fit to the sine-form. Hence those alternators which give induction curves of true sine-form are less affected than others by self-induction in the circuit, regulate better, and have a higher plant efficiency.

High Frequency Alternations.—Alternations of very high periodicity, going up to as many as 10,000 or 20,000 per second, have been studied by Spottiswoode,[2] and more recently by Tesla,[3] who has obtained some very remarkable effects. One of his alternators was of the same type as Mordey's, having numerous polar projections on either side,[4] and another was of the inductor type. With these excessively high frequencies the currents flow almost exclusively along the surface layers of conductors, instead of flowing through their entire cross-section; even straight rods of copper offering a relatively enormous impedance.



FIGS. 368 and 369.

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[1] Much attention has been given to the analysis of alternate-current curves during recent years by Perry, Ryan, Fleming, Bedell and others.

[2] *Proc. Roy, Soc.*, xxiii. 455.

[3] *American Inst. Electrical Engineers*, May, 1891. See *Electrical World*, xvi. 1891, and *The Electrician*, xxvi. 549, 1891.

[4] See *Electrical Engineer* (N. Y.), March 18, 1891,

Torque of Alternators.—A very singular result follows the presence of any lag in the current of an alternator. It was pointed out on p. 487, that where amperes flow with the volts, electric energy is being supplied by the machine, and power must be applied to drive it; but that when amperes flow against a counter electromotive-force, there electric energy is leaving the circuit and being turned into mechanical energy, helping to drive the machine. The one is the case of the generator, the other that of the motor. But now consider an alternator with the amperes lagging behind the volts, as indicated by the diagram of Fig. 370. It is clear that in consequence of this lag the amperes are sometimes flowing against the volts instead of with them. In fact, we may divide each complete period such as O X into four parts, during two of which, namely II. and IV. in Fig. 370, the amperes and volts are alike in direction, either both positive, or else both negative; during the other two parts—namely I. and III.—the amperes and volts are opposed in direction because the volts have reversed in sign, but the lagging amperes have not yet changed. Now, during the partial periods II. and IV., when there is agreement in sign, the machine is in the condition of being a generator, and will require to be driven, the currents in the armature setting up a counter torque. But during the other partial periods I. and III., when there is opposition in

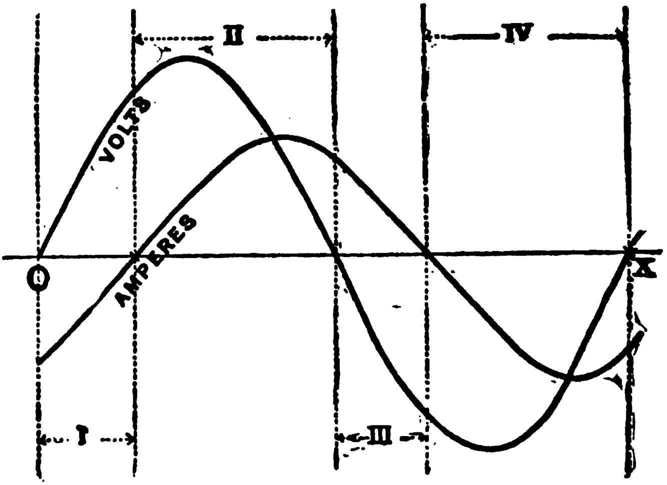

FIG. 370.—EFFECT OF LAG OF CURRENT.

sign, the machine is in the condition of being a motor, and will tend to drive itself, the torque helping it on. The conductors are consequently subjected to a racking action, alternately resisting, being driven and then helping to drive twice in each period. It is clear that if there is little lag there will be little motor action, the partial periods I. and III. being brief; whereas if there is much lag the motor action will increase. If there is lag of exactly a quarter of a period, the motor and generator actions will be equal. Similarly, if in consequence of capacity the current leads in phase, there will be motor action in partial periods. This subject may be considered in another way. The electromotive-forces change sign just as the conductors are passing (Fig. 371), from one magnetic field to another, where the lines run in an opposite direction. If the currents are in phase with the electromotive-forces, they will always tend to oppose the motion that generates them, and will reverse when the conductor passes into the reversed field as at *a*, *a*. But if the currents lag, the force exerted by the field will help on the motion of those conductors which have passed from one field to the other until such time as the currents have reversed at *b*, *b*.

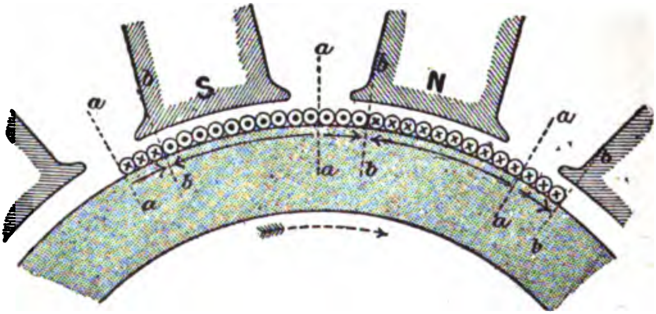

FIG. 371.

It follows that when there is a difference of phase between volts and amperes, the mean power in a cycle is equal to the difference between the power which it gives out during the partial periods II. and IV., and the power which it receives back from the circuit during the partial periods I. and III. If the phase difference is less than 90° the machine acts on the whole as a generator. If it is more than 90° the machine acts as motor on the whole. If two alternators are coupled in series, one to act as generator, the other as motor, the current will be nearly in phase with the electromotive-force in the one and almost exactly opposed to the electromotive-force in the other. This question is resumed in Chapter XXIV.

ANALYTICAL TREATMENT OF FUNDAMENTAL EQUATIONS OF ALTERNATING CURRENTS.

Beginning with the case of a loop having S_2 turns, placed at such an angle θ (measured from the initial position as in Fig. 110, where it stands right across the field), we see that it no longer encloses the whole number of magnetic lines which are present in the magnetic circuit. When we omit all account of self-induction, we may write

$$N_1 = S_2 N \cos. \theta, \qquad [I.]$$

where N_1 is the amount of flux actually enclosed by the loop in this position.

To get a complete account of the action we must now take into consideration the number of magnetic lines *induced on the circuit by itself.*[1]

If current C flow through a circuit whose coefficient of self-induction or inductance is L, the whole self-induction of the circuit will be equal to L times C; and the product L C will represent the total amount of enclosing of magnetic lines by the convolutions of the circuit.

---

[1] Neumann's mathematical investigation of the effect of considering the self-induction of the circuit in relation to a periodic electromotive-force, was published in 1845, but self-inductive phenomena had previously been studied by Henry and by Faraday.

Other mathematical investigations of alternating electric currents have been given by Weber in his *Elektrodynamische Maasbestimmungen*, and by the following :—

Koosen, *Pogg. Ann.*, lxxxvii. 386, 1852.

Le Roux, *Ann. Chim. Phys.* [3], l. 463. 1857.

Clerk Maxwell, *Phil. Trans.* 1865, p. 473.

F. Kohlrausch, *Pogg. Ann.*, cxlviii. 143, 1873.

Jamin and Richard, *Ann. Chim. Phys.* [4], xvii:, 276, 1869.

Joubert, *Ann. de l'École Normale Supérieure*, [x], 1881 ; and *Journal de Physique*, s. ii. t. ii. p. 293, 1883.

Lord Rayleigh, *Phil. Mag.*, May, 1886, p. 375.

Hopkinson, Lecture at Instit. Civil Engineers (on Electric Lighting), 1883.

" *Jour. Soc. Telegr. Engineers*, xiii.

" *Proc. Roy. Soc.*, Feb. 1887.

Abstracts of the most important of these will be found in Fleming's book on the *Alternate Current Transformer.*

But we know that if there is a current C in the circuit, we ought to write the equation in full—

$$\mathrm{N}_1 = \mathrm{S}_2\, \mathrm{N} \cos \theta + \mathrm{L\,C}. \qquad \text{[II.]}$$

Now we know that any variation in N_1 will set up induced electromotive-force, and that at any moment the electromotive-force will have the value

$$\mathrm{E} = -\frac{d\,\mathrm{N}_1}{d\,t}; \qquad \text{[III.]}$$

where we use the negative sign to show that an increase in N_1 will produce an inverse or negative electromotive-force. Any change in N_1, from whatever source arising, will set up electromotive-force. In the absence of armature reactions the only quantities whose variations contribute to the variations of N_1 are θ and C. The angle of position θ varies from 0 to $2\,\pi$ (radians); that is to say, from 0° right round to 360°, and then recurs; and its cosine therefore fluctuates between 1 and $-$ 1. The current C varies also from a certain maximum value $+\,\mathrm{C}_{max.}$ to an equal negative value $-\,\mathrm{C}_{max}$. We will neglect all the variations of the other quantities, not because these variations would not be instructive—for that would be quite untrue—but because of their lesser practical importance. Then we have

$$\mathrm{E}_t = -\frac{d\,\mathrm{N}}{d\,t} = -\frac{d(\mathrm{S}_2\,\mathrm{N}\cos\theta + \mathrm{L\,C})}{d\,t}.$$

Now suppose that while the armature loop has turned through the angle θ, the time occupied—a small fraction of a second— is t. Also take T to represent the time taken for one revolution; so that if there were n revolutions[1] per second, T will be $1 / n$ of a second. Then obviously θ will be the $\frac{t}{\mathrm{T}}$ part of a whole revolution, and as there are $2\,\pi$ radians in a circle, the angle expressed in radians will be

$$\theta = 2\,\pi\,\frac{t}{\mathrm{T}} = 2\,\pi\,n\,t = p\,t;$$

where p is written short for $2\,\pi\,n$, and called the *pulsation*.

---

[1] For multipolar machines the number of alternations is more numerous than the number of revolutions in proportion to the numbers of pairs of poles. The symbol n will in this case stand for alternations per second.

Inserting this value, and performing the differentiation, we get

$$E_t = 2\pi n S_2 N . \sin pt - L \frac{dC}{dt}; \qquad [IV.]$$

Consider this equation carefully. It shows us that when the dynamo is on open circuit, so that there is no current, then self-induction would not come in at all. The negative sign also indicates that that part of the electromotive-force which is due to the self-induction opposes the other part. Now write D for the group of symbols $2\pi n S_2 N$. Further, we know that that part of the electromotive-force which is effective in driving the current through the resistance may be calculated by simply applying Ohm's law. So if E_t, as found in formula [IV.], be the nett or effective electromotive-force at the time t, we may write $E_t = R C_t$; whence

$$R C_t = D \sin\theta - L \frac{dC}{dt}$$

This is a differential equation of the form

$$ay + b\frac{dy}{dx} = \sin px.$$

(See Boole's *Differential Equations*, p. 38.)

The solution is

$$C_t = \frac{D\cos\phi . \sin(\theta - \phi)}{R} + c\epsilon^{-\frac{R}{L}t}; \qquad [V.]$$

where ϕ is called the retardation or angle of *lag*, and has the value such that

$$\tan\phi = \frac{2\pi n L}{R}.$$

In the second term of the expression on the right-hand side of the above equation, the symbol c is a constant of integration, and ϵ is used in its common mathematical sense to represent the number 2·7182, which is the basis of the Napierian (or hyperbolic, logarithms. This second term relates only to the irregularities during the first starting of the current, and dies out as the time t increases in value. The phenomenon of inductive rush, sometimes noticed when current is suddenly switched on or off, is of this nature. In general the exponential term may be omitted.

We have therefore, got our equation for the current at time t as follows :—

$$C_t = \frac{D \cos \phi \,.\, \sin (\theta - \phi)}{R}; \qquad [\text{VI.}]$$

which should be compared with the value D sin $\theta \div$ R that the current would have if there were no self-induction. We see by comparing the two expressions that our current still follows a sine-function, but it is the sine-function not of the angle θ, but of the angle $(\theta - \phi)$; that is to say, its waves *lag* behind those of the impressed electromotive-force. Also, the amplitude of the current is reduced, because everything is going on as if the amplitude of the impressed electromotive-force had been altered from D to D cos ϕ. Or, in other words, the effective electromotive-force is equal to the part of the impressed electromotive-force as resolved along the line of the lagging current. If we substitute for cos ϕ its value $R / \sqrt{R^2 + p^2 L^2}$, we reduce the equation to the form

$$C_t = \frac{D \sin (\theta - \phi)}{\sqrt{R^2 + p^2 L^2}}; \qquad [\text{VII.}]$$

which is what we deduced from geometrical considerations.

To establish the equations for the case of a circuit possessing capacity and resistance only, we may proceed very simply to calculate what impressed electromotive-force is needed both to drive the current through the resistance and to charge the condenser. Assume $C = C_0 \sin \theta$. Let the condenser of capacity K (farads) have a charge q at any instant, then its potential will be q / K, and the corresponding electromotive-force needed at that instant to drive the current will be

$$RC + \frac{q}{K} = E.$$

But

$$q = \int C\, d\, t = -\frac{1}{p} C_0 \cos \theta, \text{ where } \theta = p\, t = 2 \pi n\, t.$$

Substituting, we get

$$R\, C_0 \sin \theta - \frac{1}{pK} C_0 \cos \theta = E.$$

Now divide both sides by

$$\sqrt{R^2 + \frac{1}{p^2 K^2}};$$

and call

$$\tan\phi = \frac{-1}{\mathrm{R}p\mathrm{K}}.$$

Then

$$\sin\phi = -\frac{1}{p\mathrm{K}} \cdot \frac{1}{\sqrt{\mathrm{R}^2 + \frac{1}{p^2\mathrm{K}^2}}}$$

and

$$\cos\phi = \frac{\mathrm{R}}{\sqrt{\mathrm{R}^2 + \frac{1}{p^2\mathrm{K}^2}}}.$$

$$\mathrm{C}_0(\cos\phi \,.\, \sin\theta - \sin\theta \,.\, \cos\theta) = \mathrm{E} \div \sqrt{\mathrm{R}^2 + \frac{1}{p^2\mathrm{K}^2}}.$$

$$\mathrm{C}_0 \sin(\theta - \phi) = \frac{\mathrm{E}}{\sqrt{\mathrm{R}^2 + \frac{1}{p^2\mathrm{K}^2}}}.$$

This indicates that the volts will lag in phase behind the current; or in other words, the current will lead in phase.

Mean Power.—The mean power is obtained by integrating the power during one period and dividing by that period, and therefore may be written

$$\frac{1}{\mathrm{T}}\int_0^{\mathrm{T}} \mathrm{E}\,\mathrm{C}\,dt = \frac{1}{\mathrm{T}}\int_0^{\mathrm{T}} \mathrm{R}\,\mathrm{C}^2\,dt = \frac{1}{\mathrm{T}}\int_0^{\mathrm{T}} \frac{\mathrm{E}^2}{\mathrm{R}}\,dt.$$

If we square the expression [VII.] found for current and substitute for the square of the sine its mean value, viz. ½, and then multiply by R we get as the mean power (in watts)

$$\mathrm{W} = \frac{2\pi^2 n^2 \mathrm{S}_2{}^2 \mathrm{N}^2 \mathrm{R}}{\mathrm{R}^2 + 4\pi^2 n^2 \mathrm{L}^2}.$$

This expression, by a well-known algebraic rule, will be a maximum for variations of R, when R is such that the two terms in the denominator are equal, or when the resistance equals the inductance. Under these circumstances the highest lag is 45°. But though this is the condition for highest plant efficiency, the regulation is, under these circumstances, bad. Hence it is better to use such a machine for lesser currents than those which would produce so great a lag.

Skin Effect.—When the frequency is high, there is a tendency for the alternate current to distribute itself unequally through the cross-section of the conductor, flowing most strongly in the surface parts. For this reason it has been proposed to use hollow conductors, or flat conductors, rather than solid round wires. But with frequencies not exceeding 100 periods per second, this tendency is negligibly small in copper conductors under one centimetre in diameter. Where the conductor is large, or the frequency high, the effect may be judged from the following instances calculated by Professor J. J. Thomson.[1]

In the case of a copper conductor exposed to an electromotive-force making 100 alternations per second, at 1 centimetre from the surface the maximum current would only be 0·208 times that at the surface ; at a distance of 2 centimetres only 0·043 ; and at a distance of 4 centimetres less than $\frac{1}{500}$ part of the value at the surface.

If the electromotive-force makes a million alternations per second, the current at a depth of one millimetre is less than one six-millionth part of its surface value.

The case of an iron conductor is more remarkable. Taking the permeability at 1000 and the frequency at 100 per second, the current at the depth of one millimetre is only 0·13 times the surface value ; while at 5 millimetres it is less than one twenty-thousandth part of its surface value.

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[1] *Elements of the Mathematical Theory of Electricity and Magnetism* (Cambridge University Press.)

CHAPTER XXIII.

ALTERNATORS.

ALTERNATORS, or alternate-current dynamos, may be classified in three sorts:—

I. Those with stationary field-magnet and rotating armature.

II. Those with rotating field-magnet and stationary armature.

III. Those with both field-magnet part and armature part stationary, the amount of magnetic induction from the latter through the former being caused to vary or alternate in direction by the revolution of appropriate pieces of iron, called *inductors*.

Alternators may also be classified into *single-phase* and *polyphase* according to whether their coils are so arranged that the currents all rise and fall in them at the same instants, or whether they have two, three or more circuits so arranged that the currents in one part are out of phase with those in another circuit. The frequency used in practice varies between 25 periods per second to 100 or sometimes 150 periods per second; but each machine is expected to work at its own proper frequency. The symbol n, used for the number of revolutions per second in the formulæ for continuous-current dynamos, is also used, in formulæ for alternate currents for the number of *periods* per second, as it corresponds to the number of complete alternations there would be if the dynamos had but one pair of poles. For arc lighting it is impracticable to work with a lower frequency than 40, though lower frequencies are quite as good for motor driving. The higher the frequency, the smaller the transformers; but very high frequencies give trouble, increasing the inductive drop in the mains. As it is requisite in alternate-current working to have so many alternations in every second, and as mechanical considerations forbid very high speeds, it is the general practice to make this class of machines multipolar, with a considerable number of poles of alternate polarity arranged symmetrically around a common centre. The number of symmetrical poles in machines of different systems varies from 12 to 48 or more.

The armatures of alternators may be of ring, drum, pole, or disk type; but the grouping of the windings is in general different from that which would be adopted for a continuous-current dynamo. The field-magnet being multipolar, a section of the armature winding which is passing a N-pole will have currents induced in it that circulate in an opposite sense to those induced in a section which is at the same moment passing a S-pole. Hence in an alternate-current ring the successive sections must be either wound or connected so as to be alternately right-handed and left-handed. In alternate-current drums the sections do not overlap one another as in ordinary drum armatures; nor do they overlap in alternate-current disk armatures.

Ring Armatures.—This type was invented in 1878, almost simultaneously by Gramme[1] and by Wilde,[2] the main difference between them being that, whilst Gramme rotated his

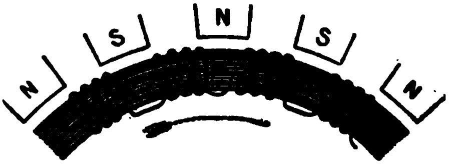
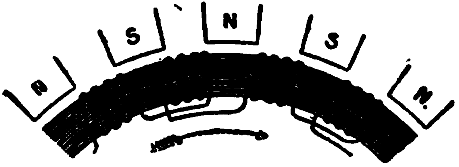


FIG. 405.



FIGS. 372 and 373.—RING-ARMATURE SERIES WINDINGS FOR ALTERNATORS.

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[1] Specification of Patent, 953 of 1878.

[2] Ibid, 1228 of 1878.

field-magnet within a large stationary ring, Wilde rotated his ring-armature within an external system of inwardly-pointing field-magnet poles (see Fig. 101, No. 28). When ring armatures are used in this type of dynamo, they must not be wound in the same manner as for continuous-current armatures. If the successive sections are to be connected up in series then they must be wound as shown in Fig. 372, alternately with right-handed and left-handed windings. If all the sections are coiled right-handedly, then they must be connected as shown in Fig. 373; for the electromotive-force induced in a coil as it passes under a N-pole will circulate around the armature core in an opposite direction to that induced in the neighbouring coil that is passing under a S-pole.

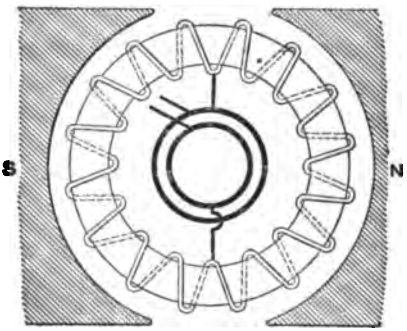


Fig. 374.—Simple Bipolar Ring Alternator.

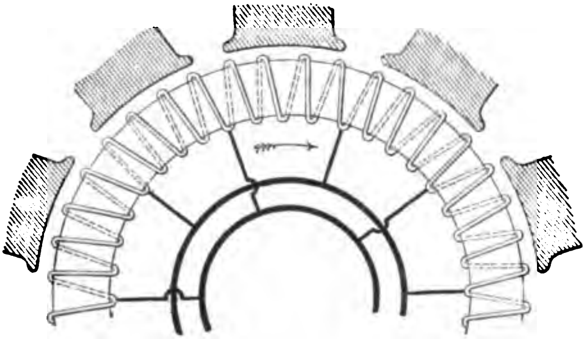


Fig. 375.—Ring-armature Parallel Winding for Alternator.

If a Gramme ring wound in the ordinary way is connected down to slip-rings from two points at opposite ends of a diameter, it will yield an alternating current when revolved in a bipolar field. In a multipolar field the ring will need multipolar connections alternately at points corresponding to the pitch of the poles. In this case, Fig. 375, the various sections of the ring are all in parallel.

A diagram of the Gramme alternator is shown in Fig. 376. The sections of the winding of this machine were four times as numerous as the poles, and might be coupled to feed four separate circuits. It is clear that the revolving poles would come past the four adjacent sections successively, so that the four alternating currents generated would differ *in phase* from one another. Gramme's was in fact a polyphase machine.

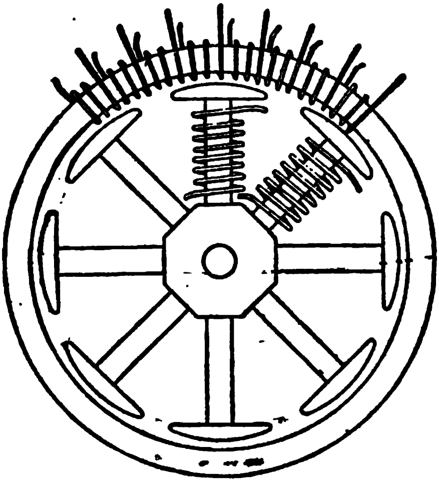


FIG. 376.—GRAMME ALTERNATOR.

One form of Gramme alternator, designed for use with Jablochkoff's candles, had four separate circuits differing 45° in phase from each other. Another ring alternator, by De Meritens, with permanent steel magnets, was a favorite about 1879. A ring armature with external magnet is used by Messrs. Ernest Scott and Mountain.

In Kapp's early alternator depicted in the former edition of this book, the ring lies between a double crown of field-magnet poles. Other ring alternators have been designed by Rankine Kennedy, who uses a discoidal ring between alternately-spaced alternate poles within an iron-clad magnet; and by Mordey, who has suggested a form with two Pacinotti rings, one laminated, as armature, one non-laminated, as field-magnet.

Drum Armatures.—So far as the active wires are concerned, they may be coupled up quite as effectively without being wound around a ring core. In Fig. 377, which is a diagrammatic picture of the early Westinghouse alternator, the windings lay on the outside of a drum core; the sections being coiled separately in temporary frames and then laid upon the surface of the core, with the ends turned down over the end core disks and firmly secured.

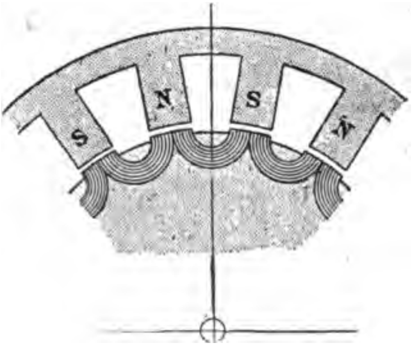


FIG. 377.—EARLY FORM OF WESTINGHOUSE ALTERNATOR.

In the recent Westinghouse machines the coils are held in deep slots in the iron of the armature. Large armatures are built up of segments, one of which is shown in Fig. 378, composed of thin mild steel stampings bolted together and assembled so as to form a core like the larger cores shown in Fig. 216, p. 288. The joint in the segments being made in the centre of a tooth does not affect the reluctance of the magnetic circuit. The coils, wound on formers, are at first of sufficient width to slip over the projections of the teeth. When in position their ends are nipped so that they fit closely and are held by the teeth from flying out. This construction is

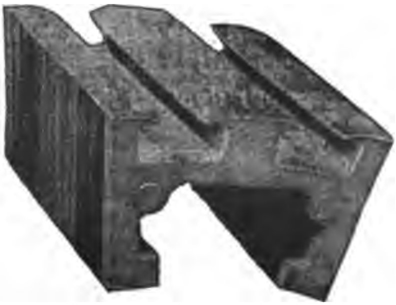


FIG. 378.—WESTINGHOUSE CORE SEGMENT.

further illustrated in Fig. 401, p. 602, which shows the wooden wedges driven in longitudinally to make the whole compact.

Fig. 379 has an internal revolving field-magnet, and as armature an external cylinder built of segmental core-plates, against the inner periphery of which the armature coils are fastened.

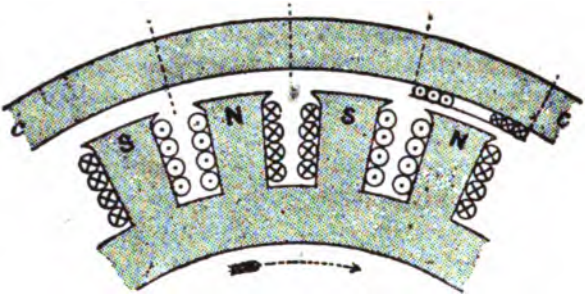


FIG. 379.—EARLY FORM OF ELWELL-PARKER ALTERNATOR.

It is but a step from this form to Fig. 380, which shows the construction of Zipernowsky, in which the field-magnet cores are made up of U-shaped stampings, and the armature cores of short T-shaped pieces which project through the coils, and are removable singly. We are thus passing away from the drum type toward that with *pole* armature.

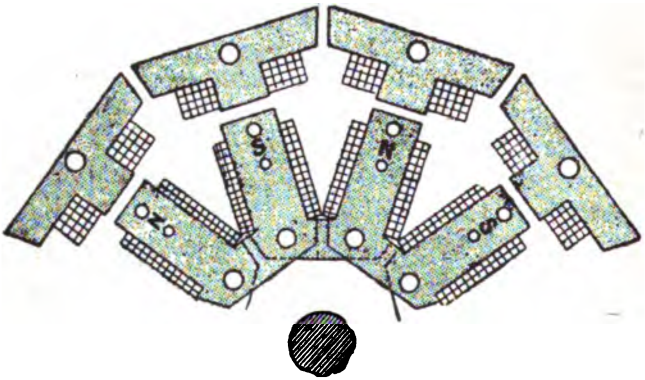


FIG. 380.—GANZ-ZIPERNOWSKY ALTERNATOR.

Hopkinson's alternator, Fig 411, p. 613, is an inversion of this design, the field-magnet being fixed and external.

Disk Armatures.—In these machines the armature coils are arranged around the periphery of a thin disk. The field-magnets consist of two crowns of fixed coils, with iron cores arranged so that their free poles are opposite to one another, with a space between them sufficiently wide to admit the armature, Fig. 383. The poles taken in order round each crown are alternately of N and S polarity; and opposite a N-pole of one crown faces a S-pole of the other crown. This description will apply to the magnets of the alternate-current machines of Wilde and Siemens, and to Ferranti's alternator. The principle will be best understood by reference to Fig. 381, which gives a general view of the arrangement. Since the magnetic lines run in opposite directions between the fixed coils, which are alternately S—N, N—S, as described above, the moving coils will necessarily be traversed by alternating currents; and as the alternate coils of the armature will be traversed by currents in opposite senses, it is needful to connect them up, as shown in Figs. 381 or 384, so that they shall not oppose one another's action.

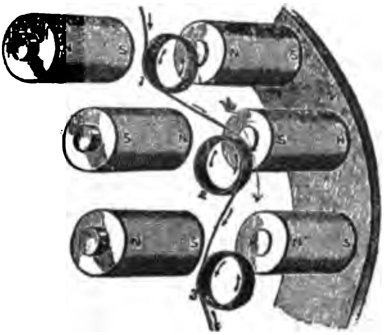
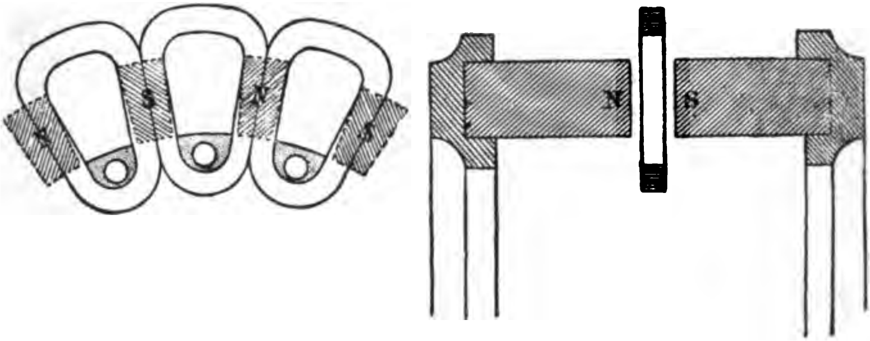


FIG. 381.—PRINCIPLE OF DISK ALTERNATOR.

Siemens' alternators, dating from 1878, realize this design with a thin disk armature built up of wedge-shaped coils. Ferranti's alternators follow the same plan, the copper coils being built up into a thin disk, as indicated in Figs. 382 and 383.

Collecting Rings.—In those alternators in which the armature part is fixed, mere terminals are required for collecting the main current. In machines with rotating armatures simple sliding connections are needed. The usual method of collecting is shown in Fig. 384. Two undivided insulated metal rings, forming the terminals of the armature coil, slide each under a collecting-brush.



FIGS. 382 and 383.—FERRANTI ALTERNATOR.

Where high voltages are used the two slip-rings should be so placed that by no accident can an attendant touch both at the same time. It is also well to provide two brushes to each ring to make contact sure. For alternators with stationary

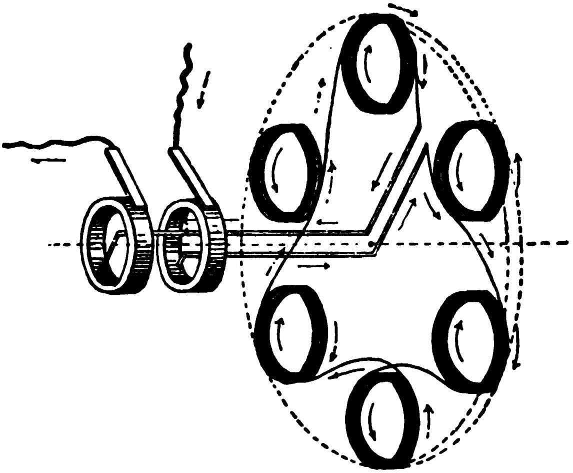
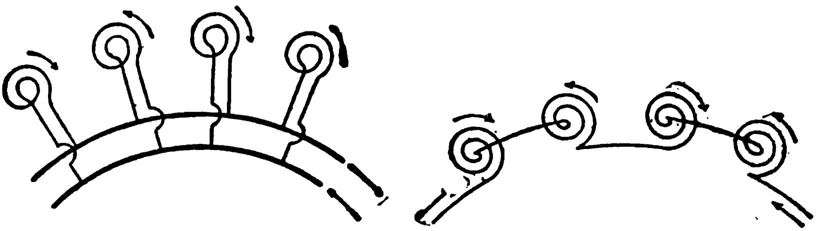


FIG. 384.—COLLECTING-RINGS OF ALTERNATORS.

armatures a similar but smaller pair of slip-rings suffice to carry the exciting current to the revolving field-magnets.

Coupling Armature Coils.—There are various ways of coupling up the coils of alternators, according to their purpose. For low-voltage work the coils may be coupled up in parallel as in Fig. 385, so as to reduce the internal resistance; whilst for supplying distant transformers and for transmission of power, in both of which cases high electromotive-force is required, the more usual mode of connecting is to join the several coils in series, as in Figs. 385 and 386.



FIGS. 385 and 386.—DIFFERENT MODES OF COUPLING UP ARMATURE-COILS OF ALTERNATORS.

Comparison of Continuous and Alternate-Current Winding.—We have seen above in the case of ring windings how a system of parallel grouping could be reached by connecting down at appropriate intervals. Precisely similar considerations apply in the case of drum windings. For instance, a 10-pole armature with 360 conductors might be wound as a re-entrant lap-winding by connecting forward at one end of the drum over a spacing of 37, and then lapping back at the other end over a spacing of 35. This is just what might be used with a 180-part commutator for continuous currents. But suppose no commutator added, and ten connections brought down at regular intervals (as in Fig. 375) to two slip-rings: it will then serve as an alternate-current armature. Instead of using this lap winding, the 360 conductors might be grouped in 10 lots of 36 each, each lot of 36 being connected (like Fig. 377), as a pancake coil, opposite a pole, and then all 10 put in parallel as before. We shall consider later the effect of concentrating the coils around polar points, as distinguished from the *distributive* winding where they are spaced out equally. If we wanted to use a wave-winding, the number 360 will not suit for a 10-pole machine. We must choose 358 with a spacing of 35 and 37 alternately. As this winding is in series with two circuits only in parallel we shall need only two connections to the slip-rings from points equidistant along the winding.

WIDTH OF POLE-FACES AND BREADTH OF ARMATURE WINDINGS.

The distance from the centre of one N-pole to that of the adjacent S-pole may be called the *pitch* of an alternator. It is desired to know what is the best proportion for the pole-faces and the windings to bear to the pitch. This matter has been discussed by Kapp.[1] It involves two questions—(1) in what way will the voltage depend on the relative width of poles and breadth of windings; (2) what proportions will give the highest plant-efficiency. If the poles are too wide, so as nearly to touch, not only is there great leakage, but the coils must be inconveniently crowded. It is obvious that for any coil to give its best result it should be so large as to embrace the whole flux of magnetic lines from each pole as it passes. If it is smaller, it contributes less to the total voltage. If it is larger it merely takes more space. Hence it is usual to make the width of the internal aperture of the coils but little less than the width of the pole, and to make the external width equal to the pitch. Compare Figs. 377, 379 and 382, in the first two of which the inner width is rather less, and in the third rather greater than that of the pole-faces, whilst the double breadth of copper in the coils is about equal to the width of the poles.

It has been shown on p. 45 that the average electromotive-force of a continuous-current dynamo may be written

$$\mathsf{E} = n\,Z\,\mathsf{N} \div 10^8;$$

---

[1] *Proc. Institution Civil Engineers*, xcvii. 1889, pt. iii.

where n was the number of revolutions per second, Z the number of conductors around the armature, and N the magnetic flux. We may adapt this to alternators, whilst keeping the two former symbols, and using N for the magnetic flux through any *one* pole, by multiplying by p the number of pairs of poles, and by a coefficient k.

So we have

$$\mathsf{E}\ (\text{virtual volts}) = kpn\, \mathsf{Z}\, \mathsf{N} \div 10^8.$$

If the fluctuations followed a sine curve, so that the virtual volts were 1·1 times greater (see p. 555) than the average volts, and the coils all joined in series (instead of two parallels), then k would have the value 2·2. The value[1] of k for various widths of poles and breadths of coils has been calculated by Kapp, with the following results; the field under each pole being supposed uniform :—

Pole Width.	Total Breadth of Copper in Coil.	k
1. Equal to pitch	Equal to pitch (covering whole surface)	1·160
2. Equal to pitch	Half of pitch (covering half surface)	1·635
3. Half of pitch	Equal to pitch (covering whole surface)	1·635
4. Half of pitch.	Half of pitch (covering half surface)	2·300
5. Third of pitch	Third of pitch (covering third of surface)	2·830

If there were no spreading of the magnetic field, No. 4 of these would be best (being also nearest sine-law). On a smooth core such as Fig. 377 or Fig. 379, the useful breadth of wires is that which would just lie between the pole-tips. The output of a machine having a given thickness of copper in the gap is proportional to the number of such wires and to the width of the pole-face; therefore to the product of the two breadths, the sum of which (if there were no magnetic spreading) would equal the pitch. Hence the output would be a maximum when the breadth of coils and width of poles were each half the pitch. But Elihu Thomson has found by experiment that, owing to the distortion of the magnetic field when the machine is running, there is an advantage in making the breadth of copper greater than this; this is by diminishing the aperture of the coils to something less than one-half the width of the pole-face.

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[1] See also Brousson on "The determination [3] E.M.F. of Alternators." *Elec. World*, 1895, xxvi. 236.

Let us consider more closely the effect of breadth of the windings in the coils of the armature. Consider a multipolar revolving field-magnet, such as Fig. 387, in which we will assume that the pole-pieces have been so shaped that the magnetic field in the gap-space between poles and armature cores is distributed in a manner so as to give a regular and smooth wave-form for the curve of electromotive-force induced in any one conductor placed in the gap. We will represent electromotive-forces which act upwards, or towards the reader, by a dot, and those which act downwards, or from the reader, by a cross placed in the section of the conductor. Then it is obvious that there will be induced electromotive-forces acting upwards in those conductors in front of which the S-pole is moving to the right, and downwards in those which the N-pole is passing. But these electromotive-forces will not be equal at the same instant amongst themselves: they will be greatest in those conductors which are most active, that is to say, in those which are passing through the strongest magnetic field. Each conductor will go through an equal cycle of inductive action, but it is clear that they come to their maximum one after the other. For convenience we will suppose this maximum to occur in each conductor as the middle of the pole passes it. Now suppose (as is usual in construction) that a number of these conductors are connected

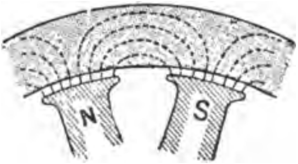

FIG. 387.

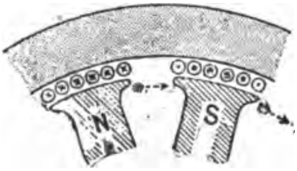

FIG. 388.

up, as in Fig. 389, to form a coil; their electromotive-forces will be added together. If a view is taken, as in Fig. 389, where we are supposed to be looking back at the poles passing from right to left, we shall understand this a little more plainly. A moment later the N-pole will come right behind the coil as in Fig. 390. This figure shows that there can be no advantage in having the inner windings of the coil much nearer together than the breadth of the pole-face, since at this instant their electromotive-forces are opposing one another. But the actual electromotive-force generated by a coil of a given number of turns would be greater if they could be all of the same size, so that all should reach their maximum action at the same instant.

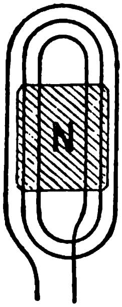

FIG. 389.

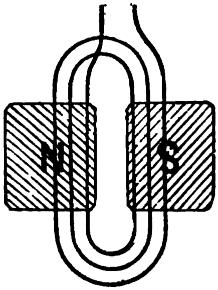

FIG. 390.

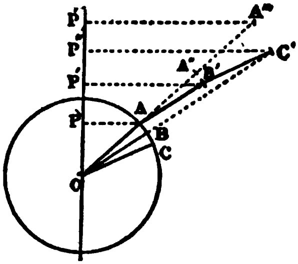

FIG. 391.

This point may be further elucidated by the use of a clock diagram. Suppose the maximum electromotive-force generated in one conductor to be represented by the pointer O A in Fig. 391. Then the projection of O A upon the vertical line O P gives the value of the electromotive-force at the instant when the angle A O P corresponds to the phase of the induction that is going on in the period. Let there be two other conductors situated a little further along so that these electromotive-forces would be represented separately by O B and O C. We have to find what the effect will be of joining them all in series. By the rules for compounding vector quantities, we shall find their resultant by drawing from A the line A B′ equal and parallel to O B, and from B′ the line

B′ C′ equal and parallel to O C. Then O C′ is the resultant; and its projection O Q upon the vertical line gives the instantaneous value of the united electromotive-force of the three conductors. Had they all been placed close up to one another at A without any difference of phase between them the resultant would have been O A‴, and this projected upon the vertical line gives O P‴ as the instantaneous value.

A numerical way of considering the matter may be useful.

Suppose each conductor to generate an electromotive-force, the virtual value of which is 1 volt: then if three such conductors are connected up in series their total electromotive-force cannot be 3 volts unless they lie so close together that they all receive their maximum values at the same time. Any spreading out of the coils *must* lower the value of the resultant electromotive-force.

It is therefore worth while to calculate a breadth-coefficient for a coil of any particular angular breadth. Let the symbol ψ stand for the difference of phase between the centre of any coil and its outermost conductor on either side. If the machine has a two-pole magnet the value of ψ is simply half the angular breadth (in radians) subtended by the coil. If the machine is multipolar, having p pairs of poles, then the angle ψ of the phase-difference will be equal to half the angular breadth (as measured on the machine) multiplied by p. Or, if the linear breadth of the coil measured along the circumference be called b, and the diameter of the machine is d, the angle ψ of the phase difference corresponding to the half-breadth will be $= b\,p \div d$. Now the average value of the virtual electromotive-force in all the conductors comprised within this breadth will be given by the formula

$$\frac{1}{\psi}\int_0^{\psi} e \,.\, \cos\gamma \,.\, d\gamma\,;$$

where e is the virtual value electromotive-force in any one conductor and γ is the angle of difference of phase between the E.M.F. in any conductor of the coil and the E.M.F. in the central conductor of the coil. If we call the part of this expression which depends on ψ the breadth coefficient, and denote it by q, then performing the integration we have

$$q = \sin \psi \div \psi.$$

In order to give some numerical values we may anticipate some of the constructions later shown. For instance, in a ring wound with four coils each covering one quadrant (as in Fig. 467),

$$\psi = 45^\circ = \text{radius}: q = 0{\cdot}90.$$

In the case of a ring wound with three coils, each covering 120°,

$$\psi = 60^\circ = \text{radius}: q = 0.82.$$

In the case of a ring wound with 6 coils each covering 60°,

$$\psi = 30^\circ = \text{radius}: q = 0{\cdot}95.$$

As an example consider a multipolar 2-phase generator, having armature conductors carried through holes in the core disks, and having 12 equally spaced holes in the repeat from one N-pole to the next N-pole. In this case six of the conductors belong to one phase, six to the other, and each group will consist of three up and three down. The three in a group occupy one-fourth the whole breadth, or are equivalent to 90° on the circle of reference: but as the conductors are confined within holes, the virtual angular distance between the two outer conductors of the three is 60°, and the half-distance 30°; whence $q = 0{\cdot}95$.

There has been much controversy whether armatures should or should not have iron cores. Iron cores are certainly inadmissible in thin disk armatures, as they would inevitably jamb against the pole-faces. Owing to the high frequency of alternation, the loss by hysteresis in machines with iron cores becomes serious, unless the magnetization is kept down below 7000 lines per sq. cm., and even then is not negligible. On the other hand, there is more loss by eddy currents[1] in the copper in machines not having iron cores.

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[1] See remarks by Elihu Thomson in comment on Kapp's paper, *loc. cit.*

MODES OF EXCITATION OF FIELD-MAGNETS.

In the older machines the field-magnets were either of steel permanently magnetized, or else electromagnets separately excited. About 1869 began the practice of making these machines self-exciting by the method of diverting a small current from one or more of the armature coils, which were for this purpose separated from the rest, this current being passed through a commutator, which rectified the alternations and made it suitable for magnetizing the field-magnets. This device is used in the "composite" alternators of the Thompson-Houston (General Electric) Co. and in those of Ganz, who also attains the effect of compounding by supplying the field-magnets with a rectified current obtained by a small transformer from the main current, to which it is proportional. Such rectifying commutators have in general the form depicted in Fig. 392, consisting of two metal cylinders, cut like crown-wheels, having the teeth of one projecting between the teeth of the other. They are insulated from one another, one being connected to one end of the wire of the armature coils that are to be used for exciting, whilst the other is connected to the other end of that wire. Two brushes are set so that one presses against a tooth of one, whilst the other presses against a tooth of the other part. An ordinary commutator having as many bars as poles may be used; the bars being connected together alternately into two sets. If the field-magnets are wound with fine wire, such a commutator may be used (in low-voltage machines) to rectify a fraction of the main current, thus making the machine virtually a self-exciting machine. It is, however, more usual to supply each alternator with a small auxiliary continuous-current dynamo termed its *exciter.*

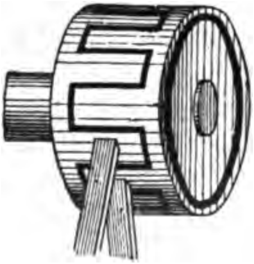

FIG. 392.
RECTIFYING COMMUTATOR.
FOR SELF-EXCITING
ALTERNATORS.

A convenient way of regulating the current or potential of alternators is to interpose a variable resistance in the exciting circuit; the resistance being operated by hand or by some automatic regulator (see Chapter XXIX.) This method is applicable either to separately excited or to self-exciting machines. In the case where separate exciters are used, the performance of the alternator may be regulated by controlling (by variable resistances, etc.) the exciting circuit of the exciter.

Alternators, when intended for supplying glow-lamps at constant pressure, whether direct at low voltage, or by transformers at high voltage, are constructed with low resistance in the armature part. Those which have also a low coefficient of self-induction would be almost self-regulating if it were not for the demagnetizing influence of the armature currents. If the field is not *stiff* (p. 393) or if there is iron in the armature, or if the armature's reaction, as measured by the number of ampere-turns per pole, is too great, the machine will require much more excitation at full load than at no load. Even in the largest machines the armature ought not to create more than 3000 ampere-turns per pole. Those armatures that have the windings deep sunk between great teeth of iron have both great self-inductive drop, and great demagnetizing action at full load. For motor-driving alternators should be chosen which have no great inductive reaction. For supplying lamps in series with a *constant current* a somewhat different type of alternator is needed, having considerable self-induction in the armature. This is attained by winding the armature coils, deeply embedded in the core, or wound on long core-plates to give considerable magnetic inertia.

The demagnetizing influence[1] of the armature current is most marked when the field-magnets are weakly excited. In the Mordey alternator (p. 619) the field-magnet is so powerful that the diminution of the electromotive-force from this cause with the full current is less than 3 per cent. of the whole, the resulting droop in the characteristic being extremely slight. The demagnetizing action depends, however,

[1] See Esson in *Electrical Review*, xviii. 248, March, 1886.

on the *phase* of the currents. If they neither lag nor lead, there will be no demagnetizing reaction, only a distortion of field (p. 75). But if they lag they will tend to demagnetize, while if they lead in phase they will help to magnetize the field. Swinburne [1] has discussed armature reactions from this point of view, and has suggested the use of condensers to produce an effect akin to compounding.

Some load-curves for an alternator have been given by Kapp (*loc. cit.*), and should be compared with Fig. 261, p. 380.

Now in an actual machine there are many armature conductors spaced symmetrically around, and these have to be grouped together by connecting wires or pieces. In the case of ring-wound armatures the connecting conductor goes through the interior of the ring-core, thus constituting a *spiral-winding*. When we go on to those cases in which the winding is entirely exterior to the core, as for drum armatures and disk armatures, we find that (as with continuous-current machines also) there are two distinct modes of procedure, which we may respectively denote as *lap-winding* and *wave-winding*. The distinction arises in the following manner. Since the conductors that are passing a north pole generate electromotive-forces in one direction, and those that are passing a south pole generate electromotive-forces in the opposite direction, it is clear that a conductor in one of these groups ought to be connected to one in nearly a corresponding position in the other group, so that the current may flow down one and up the other in agreement with the directions of the electromotive-forces. So after having passed down opposite a north pole face, the conductor may be connected to one that passes up opposite a south pole face, and the winding evidently may be arranged either to lap back, or to zigzag forward.

Wave windings were independently suggested in 1881, by Lord Kelvin and by Mr. Ferranti. But there are disadvantages in its use for high voltages, owing to the difficulty of maintaining the insulation between each "wave" and the succeeding one. In some alternators—including those of Ferranti and Mordey—the coils are joined in two parallels, not all in series, a construction which has the result of keeping the points of greatest potential difference widely apart.

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[1] *Journal Inst. Electrical Engineers*, xx. 173, 1891.

This distinction between lap-windings and wave-windings as applied to alternate-current machines, is illustrated in Figs. 393 and 394. Fig. 393 represents an 8-pole alternator with lap-winding, each "element" or set of loops extending across the same breadth as the "pitch" or distance from centre to centre of two adjacent poles. Only 24 conductors have been drawn; and it will be noticed that the successive loops are alternately right-handed and left-handed. In Fig. 394 is shown the same alternator with a wave-winding. The electromotive-force of the two machines would be precisely the same; the

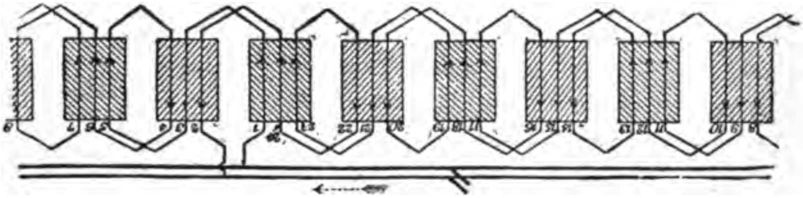


FIG. 393.—ALTERNATE-CURRENT MACHINE: LAP-WINDING.

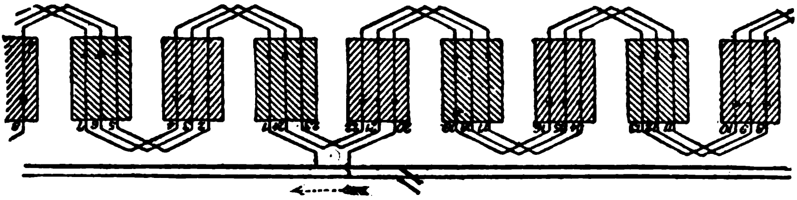


FIG. 394.—ALTERNATE-CURRENT MACHINE: WAVE-WINDING.

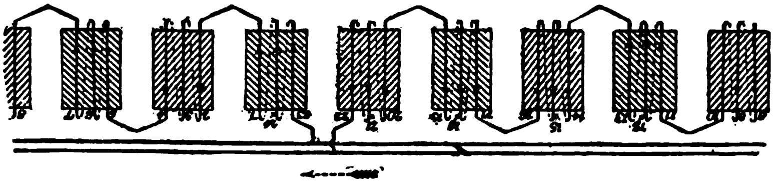


FIG. 395—ALTERNATE-CURRENT MACHINE: RING-WINDING.

choice between the two methods of connecting is here purely a question of mechanical convenience in construction and cost. The ring-winding using the same number of active conductors is shown in Fig. 395. In each case the beginning and end of the winding are connected to two slip-rings, which in these developed drawings are represented by two parallel lines. These therefore represent series or single-circuit windings.

Polyphase Alternators.—The disadvantage of making the coils broad, which was pointed out on p. 592, was experimentally discovered by Gramme. The closer the coils in any one group were huddled together, the more effective he found them. If, then, in his machine, Fig. 376, there had been only eight narrow coils—one opposite each pole—there would have been much idle space on the machine. Gramme, therefore, filled up the idle space with other coils. The sections of the winding of this machine were, in fact, four times as numerous as the poles, and might have been coupled to feed four separate circuits. It is clear that the revolving poles would come past the four adjacent sections successively, so that the four alternating currents generated would differ *in phase* from one another. Gramme knew or discovered that it would not do to join all the coils together. He only joined together those that at any one instant were opposite the poles. So there were four separate circuits each consisting of eight coils joined up in series. And these four separate windings were led off to four entirely separate circuits, each supplying a number of Jablochkoff candles with current. Gramme's alternator was unquestionably a *polyhase generator;* but there is not the slightest evidence that he at any time attempted to combine the currents of separate phases for any useful purpose, or that he knew that they could be so combined. On the contrary, he always kept the circuits separate because the several currents in them were not in phase with one another. No one, at that time dreamed of combining currents of different phase so as to get a rotatory magnetic field.

It may be remarked, in passing, that in every type of alternator there will be idle space between the groups of coils if they are wound advantageously for single-phase working.

If we make the armature with as many groups of windings as there are poles of the field we shall have a single-phase machine. If we make the coils twice as numerous as the magnetic fields we shall get a 2-phase machine. If they are three times as numerous a 3-phase machine.

The large alternators of the installation at Paddington, designed by the late Mr. Gordon (which were fully described in the first edition of this book), are 2-phase machines, with "red" and "blue" circuits kept separate. They have been at work ever since 1883.

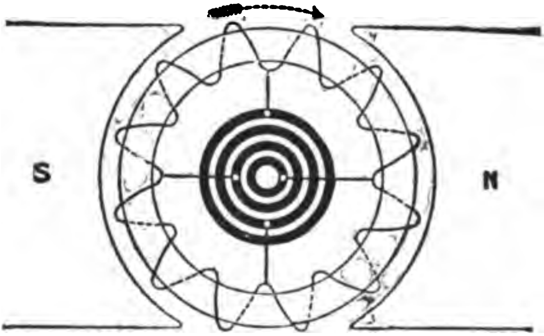


FIG. 396.—BRADLEY'S 2-PHASE GENERATOR.

A 2-phase alternator was designed by Bradley, in 1887, using in a bipolar field a ring connected at four points to four slip-rings (Fig. 396).

As the ring revolves the electromotive-forces tend always towards the highest point. Two separate alternate currents may therefore be taken from this machine, but they will differ by a quarter-period or be "in quadrature," as represented in Fig. 397.

A 3-phase alternator might have been made by connecting the ring to three slip rings at points 120° apart. Gramme indeed wound some of his rings with three independent sets of coils. Such a machine will yield three currents in three separate successive phases. If these were grouped as in

Fig. 398, we might join up the A coils together into one circuit (the coils being wound or connected alternately right-handedly and left-handedly); the B coils being similarly joined up into a second circuit, and the C coils being joined into a third. It is clear that in each set the electromotive-forces would rise and fall in regular succession, and that the electromotive-force in B would not rise to its maximum until after that in A had passed its maximum and was falling. In fact the differences of phase might be represented by the three curves of Fig. 399. Since the angular distance around the machines from one N-pole to the next N-pole corresponds to one whole "period" (p. 549), or to one complete revolution of 360° on the imaginary circle of reference (Fig. 351), we see that these three currents will

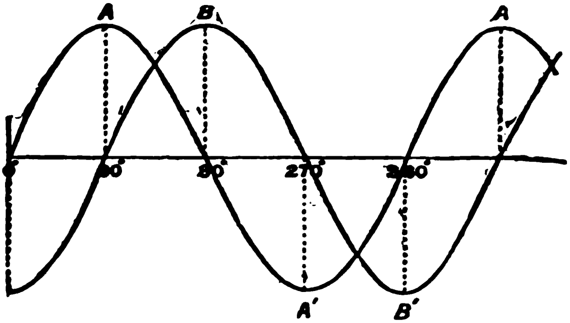


Fig. 397.—Two Alternate Currents differing by a Quarter Period.

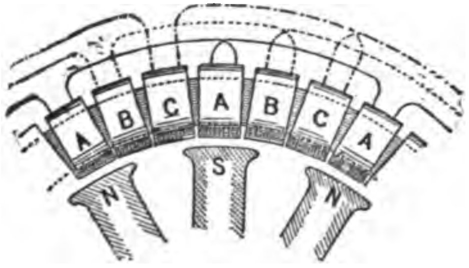


Fig. 398.— 3-phase Generator.

differ in phase from one another by 60°. If we had a separate outgoing and return wire for each of the three circuits, we should need no fewer than six lines from the machine to the (3-phase) motor which it supplied. But as will be seen (p. 669), by adopting proper methods of grouping, this complication is unnecessary, the number of lines being capable of being reduced to four or to three. If an earth return were admissible the number of actual line wires might even be reduced to two.

Not only does the adoption of a polyphase winding lead to certain advantages in the operation of motors; it also effects a saving in the cost of the machines. By winding a second set of circuits on the otherwise idle spaces on the core we may double the output of the machine. It will take twice as much horse-power to drive: it will give out twice as much horse-power electrically. But it will not cost twice as much, nor take up any more space. Goerges states that a 3-phase machine was found to give an output 2·73 times that of the same machine with a continuous-current armature.

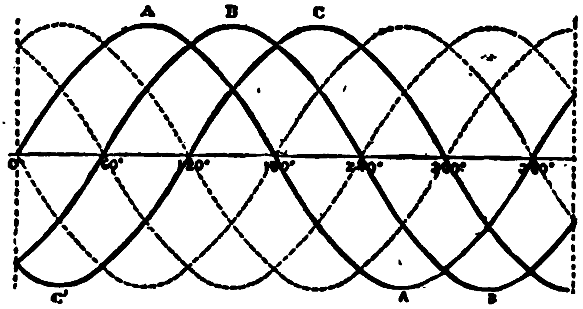
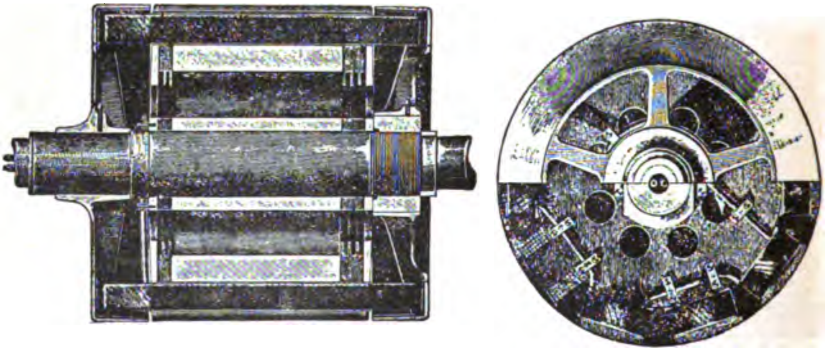


FIG. 399.—THREE-PHASE CURRENTS DIFFERING 60° IN PHASE.

CONSTRUCTION OF ALTERNATORS.

Although some excellent alternators have been made of the thin disk type by Siemens, Ferranti, Mordey and Crompton, there is at present an obvious preference on the part of electrical engineers for machines of other types whenever large outputs are required. The racking strains to which the armature conductors are subjected render difficult the task of giving to the thin disk the mechanical strength it needs without sacrificing good insulation, or using constructions that would heat by reason of eddy-currents. Hence the majority of makers use iron core-disks in the construction of their armatures: and whether the armature revolves or stands still a sunk-winding is almost universal.

In Fig. 216 were shown some of the core-disks used by the Westinghouse Co. Those with a few large teeth are for alternators. Figs. 400 and 401 show the construction. The coils are wound on special formers and bent into their places; then secured by wooden wedge-pieces. In the largest machines the armature cores are built up of stampings assembled in sections, one of which is shown in Fig. 378. Fig. 402 shows a general view of a 450-kilowatt alternator of the Westinghouse standard type, having 30 narrow radial poles of elongated section surrounding an armature which is provided not only with the two slip-rings but with a rectifying commutator to furnish a small exciting current. The poles are of laminated steel cast solid into the outer yoke. The armature cores have 30 teeth to correspond. In many modern machines, however, the armature is fixed, and surrounds an



FIGS. 400 and 401.—SECTION OF WESTINGHOUSE ALTERNATOR ARMATURE.

internally revolving magnet. In this case the armature cores take in general one of the two forms shown in Figs. 403

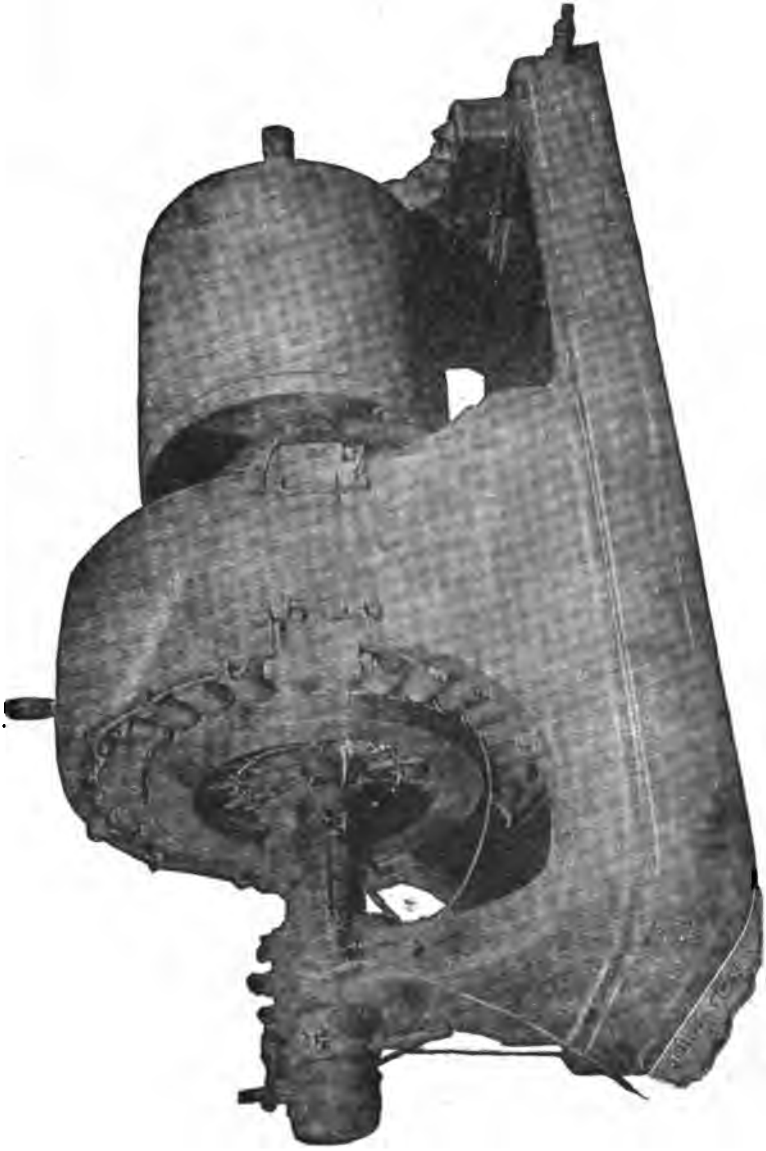


FIG. 402.—450 KILOWATT ALTERNATOR (WESTINGHOUSE CO.).

and 404. The pierced form is distinctively Swiss. Such core-rings are built up in segments, and may be wound in various ways. For low-voltage machines stout conductors may be drawn in and connected up in wave-form. For high voltages lap-windings are more usual, a number of turns being looped through two of the holes situated at a distance apart about equal to the pitch of the poles. Brown has introduced the practice of arranging these end parts of the loops where they emerge outside the core rings in two sets in different planes. This construction, which is applicable to all alternators whether for single-phase, 2-phase or 3-phase work, and to motors as well as generators, may be noticed in the coils in Plate XVIII. Though a detail it is of great use in obviating risks of short circuits. In Fig. 405 this construction is diagrammatically displayed, showing how both the A set and B set of windings in a 2-phase generator may be grouped so as to utilize for each lap two sets of holes side by side. This has some advantages over using single holes of very large size. These would interfere more with the magnetic circuit and tend to set up greater heating in the polar parts of the field-magnet.

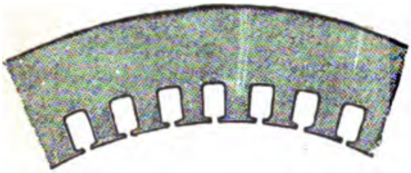


FIG. 403.

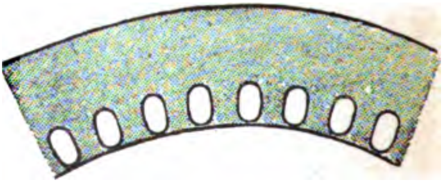
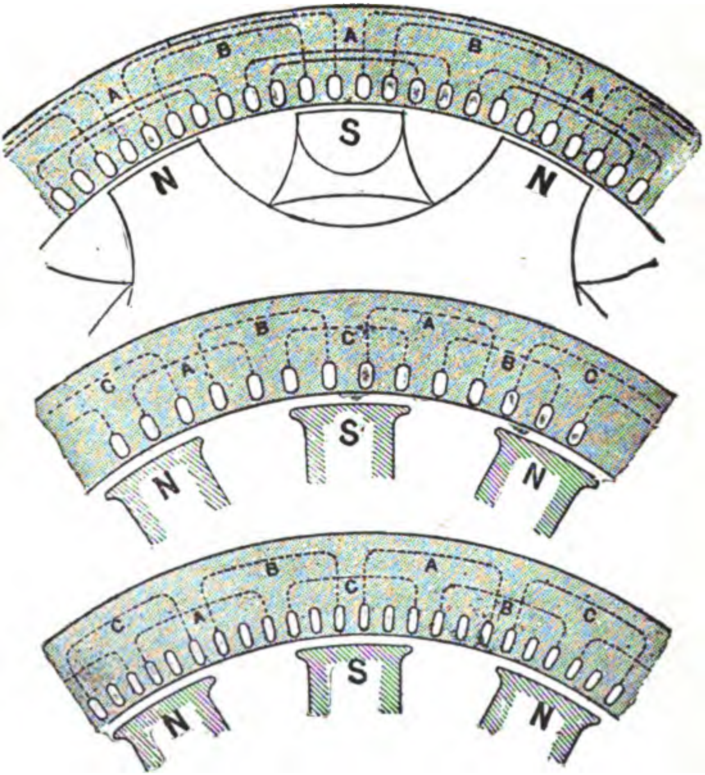


FIG. 404.

Fig. 406 shows an adaptation of the method of arranging the windings of a 3-phase generator, so that the loops of the coil can still be situated in two planes. The A coils will of course be connected together in series, though they lie alternately in the inner and in the outer positions; and so likewise the B and C coils.

Fig. 407 shows how the core-rings may be utilized for a 3-phase generator (or motor) with a winding in which all the holes are not employed. This winding was used to save the necessity of making a fresh set of stamps for the core-disks. The magnetic reactions are less, when the unused holes are left in the spaces as shown, than would be the case if the core-rings at these parts were not pierced.

Another variety of the same construction may be noticed in Plate XVII., where one of the sections of the core is shown swung outwards for cleaning.



Figs. 405, 406, 407.

In designing alternators the same general rules are to be followed as govern the design of continuous-current dynamos; but owing to the higher frequency of the reversals of magnetism a lower density of flux—say from 6000 to 7000—is to be observed in the laminated armature iron. The coefficient k, which comes in the fundamental formula, having been determined by experiment in any given type, can be used in calculating machines of similar type. In calculating the excitation to be provided for the field-magnets, allowance must be made for the inductive choking action of the armature windings, as well as for the demagnetizing (p. 559) reaction of the armature currents; both these causes conspiring to produce an "inductive drop." Suppose an armature winding to have been calculated for 2000 volts on open circuit, at normal speed and field, and that the full current is to be 20 amperes. Some experiment must be made to ascertain the additional volts necessary to drive 20 amperes, not only through the resistance of the field but against its self-inductance. An experimental determination of this may be made by measuring with a voltmeter the volts actually needed (at the proper frequency) to send this current through the armature. Another and better experimental method is to short-circuit the machine through an amperemeter, and then drive it at the proper speed with field-magnets at first unexcited, gradually increasing the excitation until normal current is reached. Then open the circuit and measure the volts which at such excitation the armature generates. The next step after having found this reactive electromotive-force is to reckon out the additional excitation. Suppose that the experiment in question had shown the reactive electromotive-force to be 880 volts, then since they are in quadrature with the effective electromotive-force of 2000 volts, it will be needful that the impressed electromotive-force at full load should be at least

$$\sqrt{880^2 + 2000^2} = 2184 \text{ volts};$$

for which amount the full-load excitation must be calculated upon magnetic circuit principles. An example relating to a Kapp alternator was given on p. 656 of the previous edition.

Asynchronous Generators.—It has been found by several experimenters independently—amongst them Mr. C. E. L. Brown, and the engineers of the General Electric Company, at Schenectady, New York—that asynchronous motors (see p. 685), whether polyphase or monophase, can act as generators provided they are mechanically driven at a slightly higher speed than that of synchronism. But it is not possible to work a circuit with only one such machine to be used as a generator—it is not self-exciting. There must be an alternate or polyphase current already supplied to the mains or terminals. It would probably be convenient in those central stations where the load is apt to show very sudden increase, to use one or more asynchronous generators along with other alternators, as the asynchronous generator might be kept turning as a non-loaded motor at a speed just below synchronism until required. On merely quickening up the speed of its engine (without waiting to "synchronize") it will begin to work as a generator, its electromotive impulses synchronizing perfectly with those of the circuit, though its speed is not synchronous.

EXAMPLES OF ALTERNATORS.

Gordon's Alternator.—Gordon's alternator was described and figured in the earliest editions of this book. It has twice as many coils in the fixed armatures as in the rotating magnets, there being 32 on each side of the rotating disk, or, in all, 64 moving coils; while there are 64 on each of the fixed circles, or 128 stationary coils in all. The latter are of an elongated shape, wound upon a bit of iron boiler-plate, bent up to an acute V-form, with cheeks of perforated German silver as flanges.[1] The result of thus arranging the coils in two sets, is that there are two distinct currents differing in phase by a quarter period. The Paddington station, equipped by Gordon in 1883, was the first 2-phase station.

Kapp's Alternators.—The multipolar ring-armature alternators of Kapp were described in detail in the previous edition, and scale drawings were given of a 60 kilowatt machine built at the Oerlikon works. More recently Mr. Kapp has designed a new alternator for Messrs. Johnson and Phillips. The construction is shown in Fig. 408. The

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[1] For further details of the Gordon dynamo, see Mr. Gordon's *Practical Treatise on Electric Lighting* (1884), p. 162.

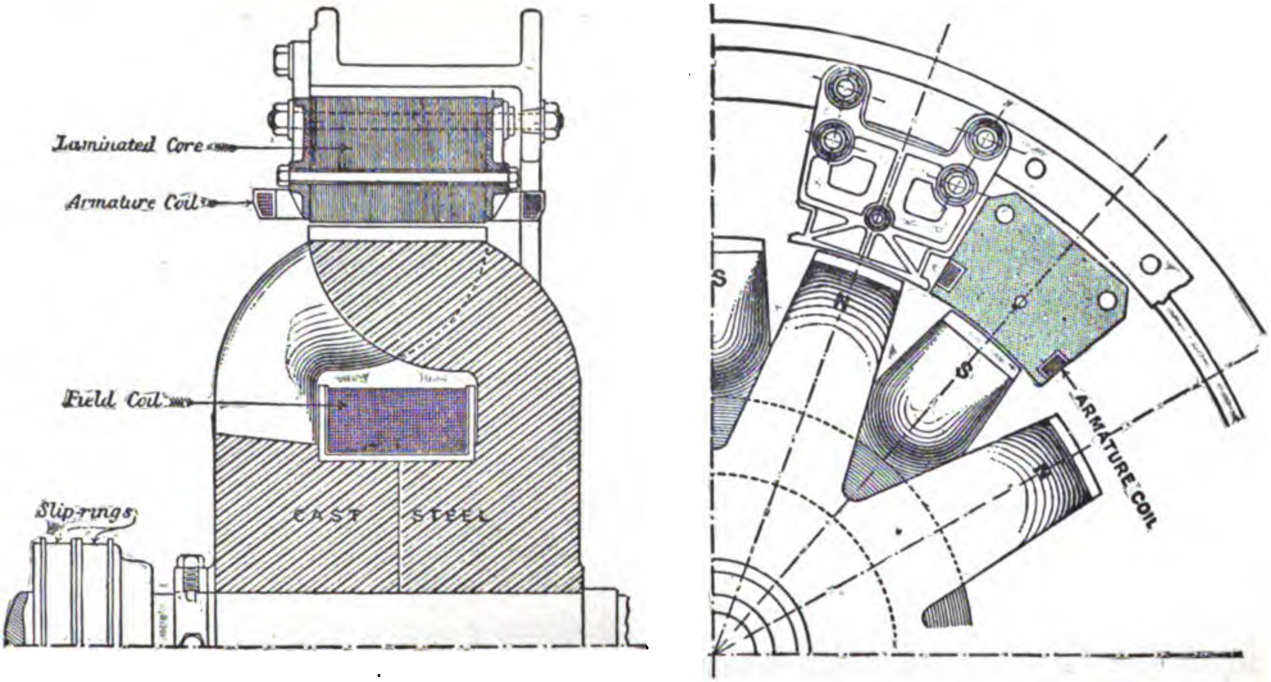

FIG. 408.—KAPP'S ALTERNATOR.

armature core is built up of stampings assembled in removable segmental blocks. Around each block of core in end notches is wound a section of the armature coil. The armature consequently has considerable self-induction. The field-magnet is on the same plan as that of the Lauffen alternators described later (p. 631), having but a single coil for excitation.

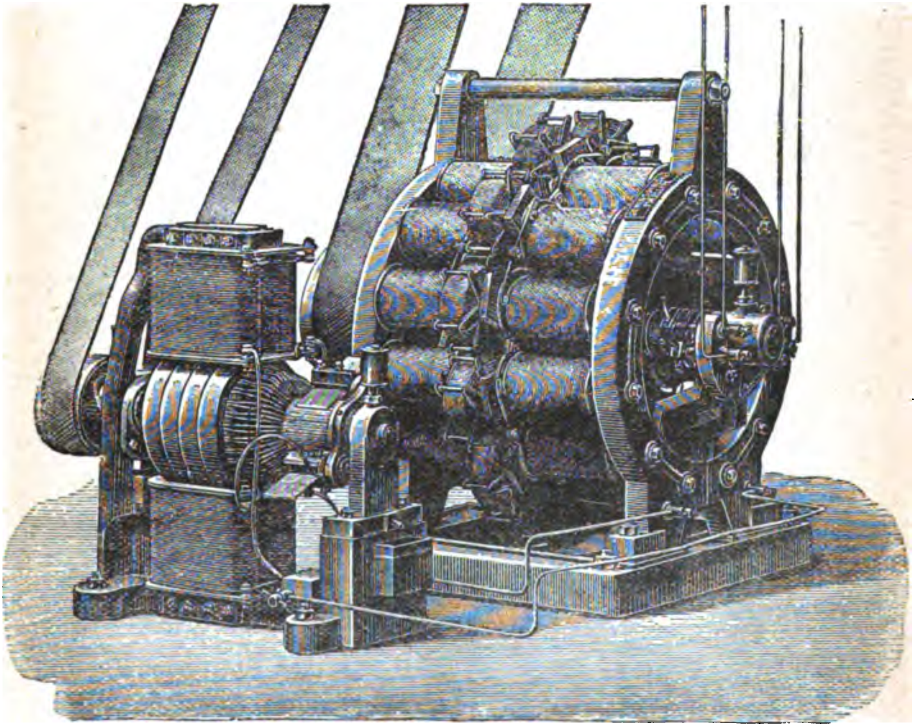

FIG. 409.—SIEMENS ALTERNATOR, WITH ITS EXCITER.

Siemens Alternators.—Messrs. Siemens and Halske were early in the field in 1878 with alternators designed by von Hefner Alteneck, having a disk-armature (see Fig. 409), in which the coils are wound usually without iron, upon wooden cores. Copper ribbons insulated from one another by strips of vulcanized fibre are used for the coils; the connections being made by soldering the strips with silver solder. In some forms of the machine, the individual coils are enclosed between perforated disks of thin German silver. In cases where large currents are required, at no great electromotive-force, the coils are coupled up in parallel instead of being united in series. In Fig. 409 a small continuous-current machine of vertical pattern, such as was described on p. 404, is shown in action as an exciting machine to furnish the magnetizing currents to the stationary field-magnets of the alternator.

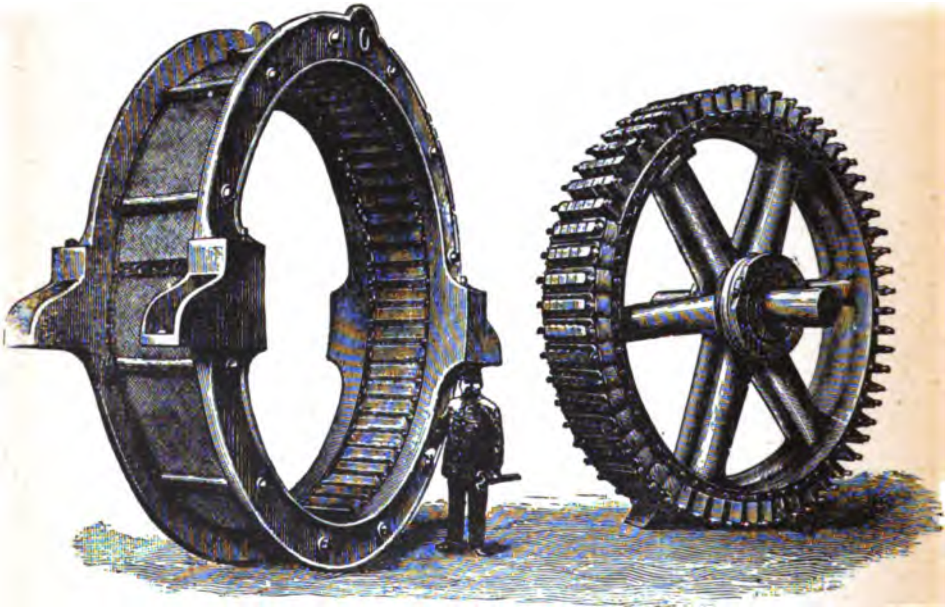

FIG. 410.—SIEMENS AND HALSKE ALTERNATOR.

More recently Messrs. Siemens and Halske have returned to a form with multipolar rotating field-magnet and fixed external armature. The large 330 kilowatt machine shown at Frankfort in 1891 is depicted in Fig. 410. The field-magnet consists of 60 bobbins with laminated cores built upon the rim of a fly-wheel, 3·7 metres in diameter over all; whilst the armature ring is 4·6 metres (14 ft. 9 in.) in external diameter. When running at 100 revolutions per minute, it yields 165 amperes at 2000 volts. The construction of the armature is as follows:—A laminated ring of 60 segments, each built up of straight iron plates stamped with end-projections, is held together firmly in a cast-iron frame. Each segment before being put in place is wound with 20 turns of a conductor made of stranded copper wire compressed to a square section, each wire in the strand being lightly insulated with a coat of enamel. The ring thus formed is 4·6 metres in diameter, and 50 centimetres in width parallel to the axis; the end projections of the core-plates constituting 60 internal teeth. It is therefore simply a laminated Pacinotti ring with sections coiled alternately right and left-handedly. Any one of the sections can be removed singly for repair. The laminated magnet-cores carry 76 windings each, and receive a current of 56 amperes at 70 volts for excitation.

The large 3-phase alternators recently made for the central station at Chemnitz by Siemens and Halske, have a general construction resembling Fig. 406.

Ganz-Zipernowsky Alternators,—Various forms have been built[1] by Ganz and Co., of Buda-Pesth, chiefly from the designs of M. Zipernowsky. The general principle of these machines has already been described on p. 584; but some have been otherwise constructed. At Frankfort, in 1891, a large Ganz alternator was shown by the Helios Co.,[2] of a capacity of 400 kilowatts, giving 200 amperes at 2000 volts at 125 revolutions per minute. The armature consisted of 40 T-shaped punchings, like Fig. 380, surrounded with coils each working at 100 volts, the whole being coupled up in two series of 20 each. The rotating field-magnet is 299·2 centimetres in diameter, and 38 centimetres wide. The electrical efficiency is given at 95·6, and the nett efficiency at 91·5 per cent. Four very fine examples of the Ganz alternator exist in the central station of Rome,[1] each being of 320 kilowatts capacity driven direct at 125 revolutions per minute by separate compound engines of 500 H. P. each. They have rotating field-magnets with 40 radiating poles of solid iron, the diameter being over 9 feet. The interior diameter of the armature ring frame is about 9½ feet, the core being built up of sheet iron and paper as described. There are 40 coils, each generating 50 volts, all united in series, and capable of carrying 200 amperes, the wire being 6 mm. in diameter. The bobbins on which the magnet coils are wound, are made of split rectangular zinc formers about 15 inches high and 20 inches wide, the windings being more numerous toward the outer end. The armature windings, 30 in each coil, are contained on vulcanized fibre frames 19 inches long, 10 inches wide, and 2 inches deep, and are clamped in place by skeleton bronze frames.

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[1] See *Centralblatt für Elektrotechnik*, xii. 554, 1889; also *Electrical Review*, xv. 70, 1884; xvii. 115, 1885; *Electrician*, xxv. 258, 1890; *Electrical World*, xiii. 297, 1889; xvi. 73, 1890; *La Lumière Électrique*, xxxi. 121; and xxxii. 159 and 582, 1889.

[2] See description by Mr. Esson, and cut, *Electrical Review*, xxix. 508, 1891.

Hopkinson Alternator.—This machine has fixed external multipolar magnets, with a width of pole-face exceeding three-fourths of the pitch. The armature wires are coiled upon short polar projections of laminated iron having extended faces. The machine is shown in Fig. 411. Its exciter is mounted on a bracket to run on the same shaft.

Owing to the almost complete continuity of the iron of the magnetic circuit, and the high peripheral speed which the construction of the machine admits of, an exceedingly high efficiency is obtained. The following are particulars of machines of this type constructed by Mather and Platt for the Salford central station.

No. of poles	20
Revolutions per minute	450
Output	40 amperes at 3000 volts.
Resistance of all magnet coils in series	7·4 ohms.
Resistance of armature coils in series	0·8 ohms.
Exciting current required through magnets at full load	10 amperes.
Hence *electrical efficiency* at full load	98·4 per cent.

[1] See description by Prof. Fleming in the *Electrician*, xxv. 317, 1890.

In spite of their high self-induction, these machines are suitable for working in parallel, and have so much armature reaction that they can be short-circuited with perfect safety.

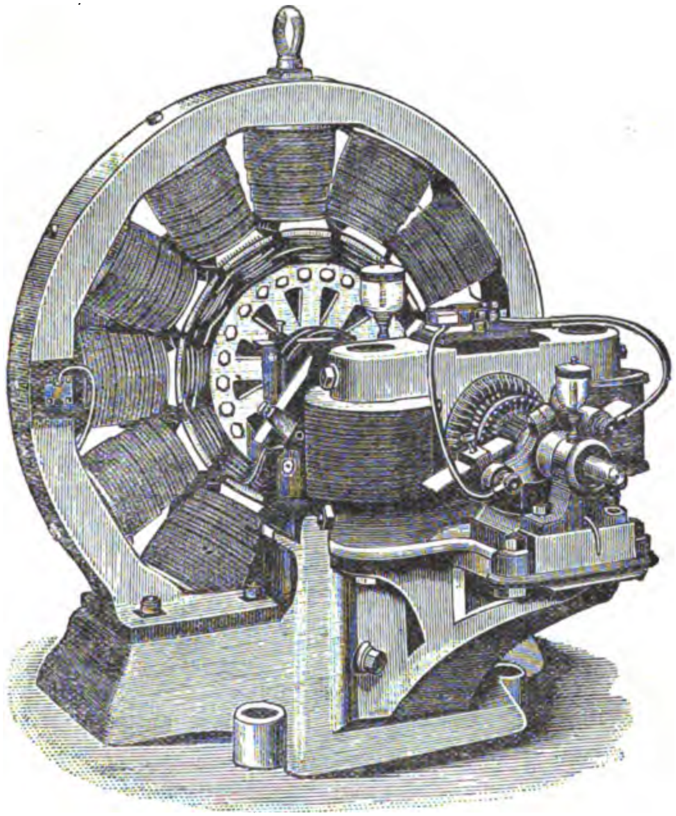

FIG. 411.—HOPKINSON ALTERNATOR (MATHER & PLATT).

Ferranti's Alternator.—This machine, as brought out in 1882, was based on the joint but independent proposal of Lord Kelvin and Mr. S. Z. de Ferranti to substitute wave-windings for coils.

In the machine as constructed at that date,[1] the field-magnet consisted of two crowns of alternate-poles, precisely as in the alternators of Wilde and Siemens; and the armature consisted of strip copper bent into a wavy star form. There were eight loops in the zigzag (as shown in Fig. 412), and on each side were 16 magnet poles; so that the current flowing radially outward past a N-pole flowed radially inward past a S-pole. The copper strip was wound round on itself (with insulation between) in many layers; the limbs of the star being held in place by insulated bolts passing through star-shaped face-plates. The advantage of the armature of zigzag copper was supposed to lie in its strength and simplicity of construction.

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[1] See Specification of Patent, No. 3702 of 1883; and for later details, No. 702 of 1887.

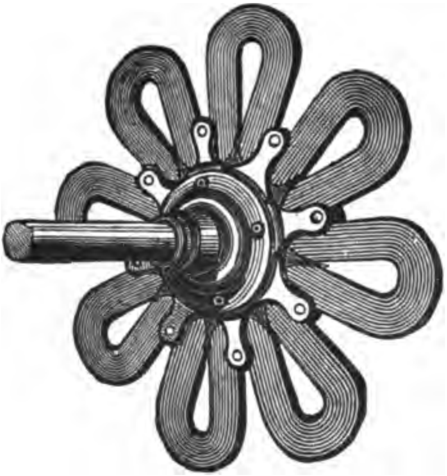
FIG. 412.—FERRANTI ARMATURE (1882).

In the later alternators of Ferranti the zigzag mode of winding has been entirely abandoned, and the coils are wound separately and then assembled into a disk. The mode of construction is explained by the figures which follow. Each coil is wound upon a rigid core. The cores are constructed of brass strips spreading fan-wise, with asbestos between, brazed solidly together at one end, and united to a brass piece drilled with an aperture A (Fig. 413). The winding, the inner end of which is soldered to the brass piece, is of ribbon copper slightly corrugated to secure greater rigidity, wound with a tape of thin vulcanized fibre between. The coils are mounted in twos in brass coil-holders, depicted at D, Fig 415, into which, with interposed layers of mica and fibre, they are secured by bolts which pass through their eyes. The two coils in each holder are separated mechanically and electrically by interposing a piece of fibre of the form shown at H; but the holder constitutes a metallic connection from the

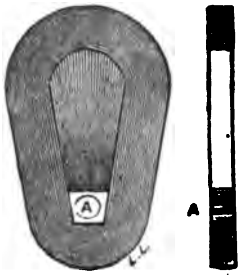

FIG. 413.—SINGLE COIL OF FERRANTI ARMATURE.

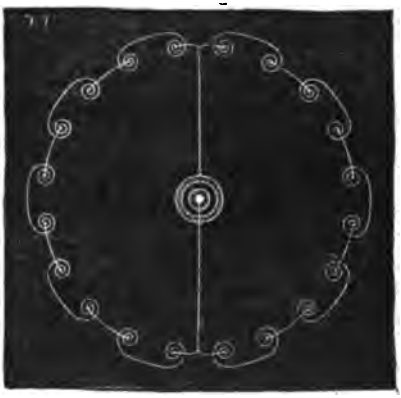

FIG. 414. CONNECTIONS OF FERRANTI ARMATURE.

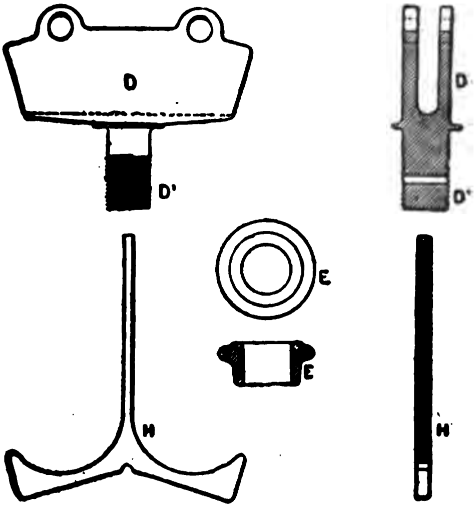

FIG. 415.—DETAILS OF FERRANTI ARMATURE.

eye A of the one to the eye A of the other. Consequently, a current circulating from outside to inside of one coil must circulate from inside to outside of the other. The outside end of each coil is joined to the outside of the nearest coil in the next holder. The holders must of course be insulated, and yet held mechanically and firmly. For this purpose they are provided with a tail-piece D′, of circular section, which passes through a porcelain bush E, and is threaded to receive a metal foot which is further secured by a pin passing through D′. The tail-piece, protected by its porcelain bush, passes through the rim of a strong foundation ring, having apertures into which the metal feet are inserted, but which are much wider and longer. The gap between them is then filled up by pouring in a molten compound of sulphur and powdered glass, which secures and insulates them. On the side of each coil-holder projects a small oblique wing, to promote ventilation. In all the larger machines the coils are connected up, as shown in Fig. 414, in two series, which are joined together in parallel. This grouping is effected by placing all the coils in one half circumference right-handedly, and in the other left-handedly, and is adopted so as to keep widely apart the coils that differ most in their potentials.

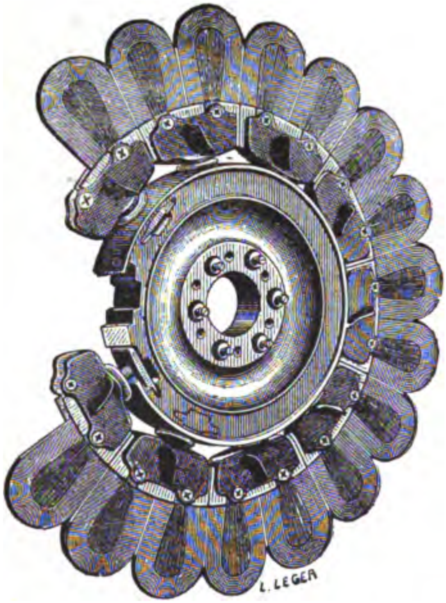

FIG. 416.—FERRANTI ARMATURE, SHOWING MODE OF MOUNTING COIL-HOLDERS.

Two copper rods pass inwards from the tail-pieces of two of the coil-holders at opposite ends of a diameter, and are led to the collecting arrangements which are mounted on the end of the shaft.

Fig. 417 relates to a 225 kilowatt Ferranti alternator, and gives a view of half the armature and half the field-magnet. Here it is seen how the copper connector D^2 passes from

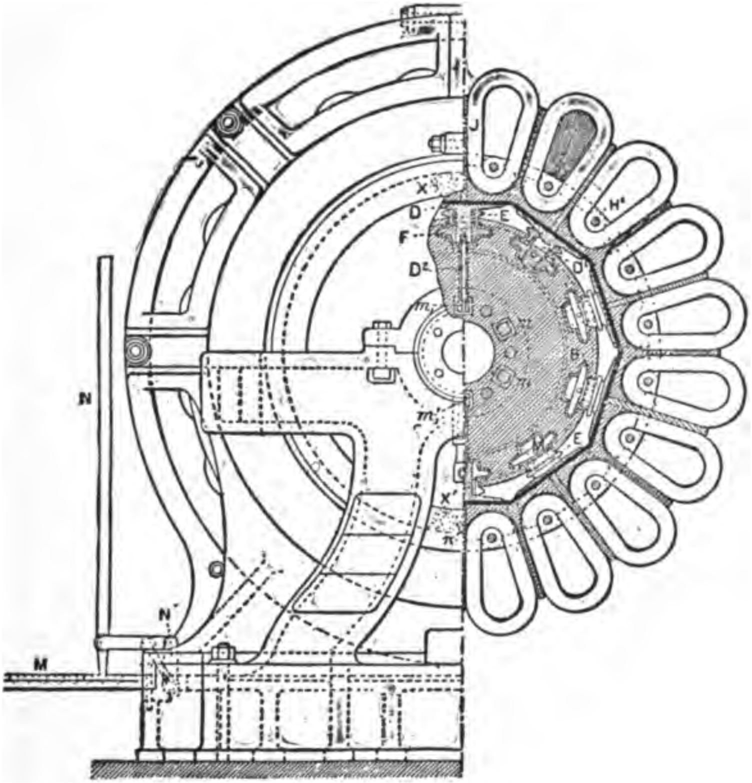

Fig. 417—Ferranti Alternator (225 kilowatts). Scale $\frac{1}{20}$.

the coil-holder D to m_1, a bolt uniting it to the collecting apparatus. The cut also shows how the field-magnet is built in two separate halves, each of which can be racked laterally aside by a lever N and rack M to expose the armature for cleaning or repairs. The speed of this machine is 350 revolutions per minute, and the diameter of the armature 5 feet 6 inches.

Fig. 418 represents on a scale of 1 : 72 the 1000 kilowatt alternators as used at the Deptford lighting-station. These machines, capable of giving 100 amperes at 10,000 volts, when running at 120 revolutions per minute, are driven by rope-gearing from engines of marine type. The pulley, which has grooves for 27 ropes, is nearly 10 feet in diameter, and over 10 feet long. It is built in two parts N and N_1, united by bolts at *a*, and is keyed to the middle of the shaft between two bearings *y* mounted on pedestals which curve inwards at both ends. The journals are of unusual length, and the bearings swivel upon spherical seats. End play is prevented by collars at the outer ends of the shaft. The exact position of the pulley upon the shaft can be adjusted by a central screw collar *c*, turned by a handle U. This adjustment is rendered necessary because the armature is mounted upon the end rim F of the pulley itself, over-

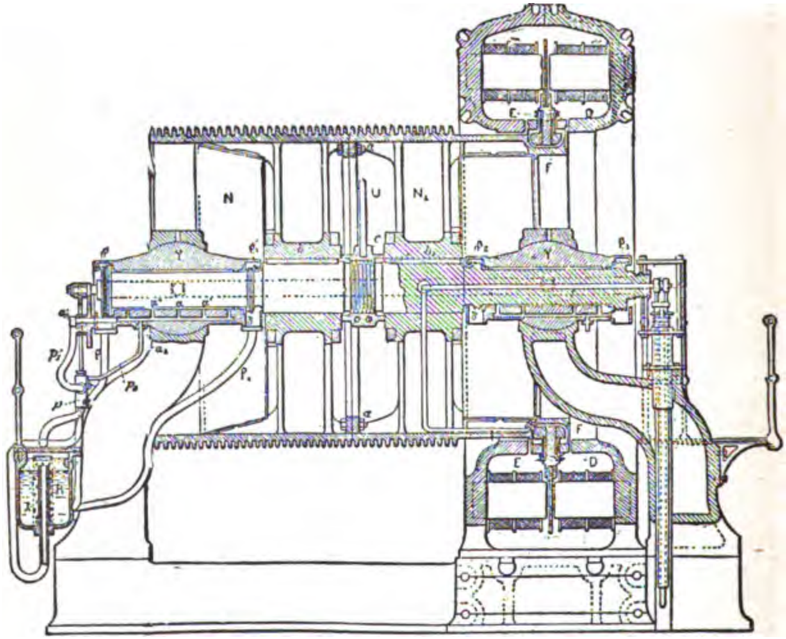

FIG. 418.—FERRANTI ALTERNATOR (1000 KILOWATTS). Scale $\frac{1}{72}$

hanging the bearing; and, as the clearance between the armature coils and the magnet pole-faces is very small, any wearing of the bearings might cause the armature-coils to come dangerously close to the pole-faces. The coil-holders and porcelain bushes are shown at D and E. The magnet-poles are held in a large external cast-iron frame. There are 48 poles in each crown, of alternate polarity. The faces are covered with caps of thin ebonite to protect against spark discharges from the coils. The armature coils, also 48 in number, are each capable of generating about 420 volts, and will carry a current of 50 to 55 amperes without undue heating. The mean diameter of the armature is 15 feet, and its peripheral speed is therefore 5850 feet per minute. The thickness at the working part is only ¾ inch. Owing to the mode of driving the armature the insulated copper connections must pass through the bearing, and are therefore carried along in a channel through the shaft. The most elaborate precautions are taken against the possibility of a stoppage arising from over-heating of the bearings. There is a double circulation of water and of oil. On the end of the shaft opposite to the collecting apparatus an eccentric works an oil-pump *p*, which pumps oil through a filter out of the reservoir R under the platform, and distributes it under pressure to the oil-ways *a* in the bearings, whence it returns to the reservoirs.

The alternators lately constructed by Mr. Ferranti for the Portsmouth central station [1] are of entirely different construction, and follow very closely the lines of Brown's machine, Plate XVII.

Mordey's Alternator.—This striking form of machine, first brought out in 1888, is constructed by the Brush Electrical Engineering Company, of London. One of small size is depicted in Fig. 419, while on Plate XIV. are given drawings of one of the 200 kilowatt machines,[2] lately erected at the Leicester lighting station.

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[1] See *Electrician*, xxxiii. 157, 1894.

[2] See *The Engineer*, lxxx. 57, July 19, 1895. The figures given in plate XIV. have been reproduced from this article.

The characteristic features of the Mordey alternator are the stationary thin-disk armature, and the solid revolving field magnet. In the latter, though there are two crowns of

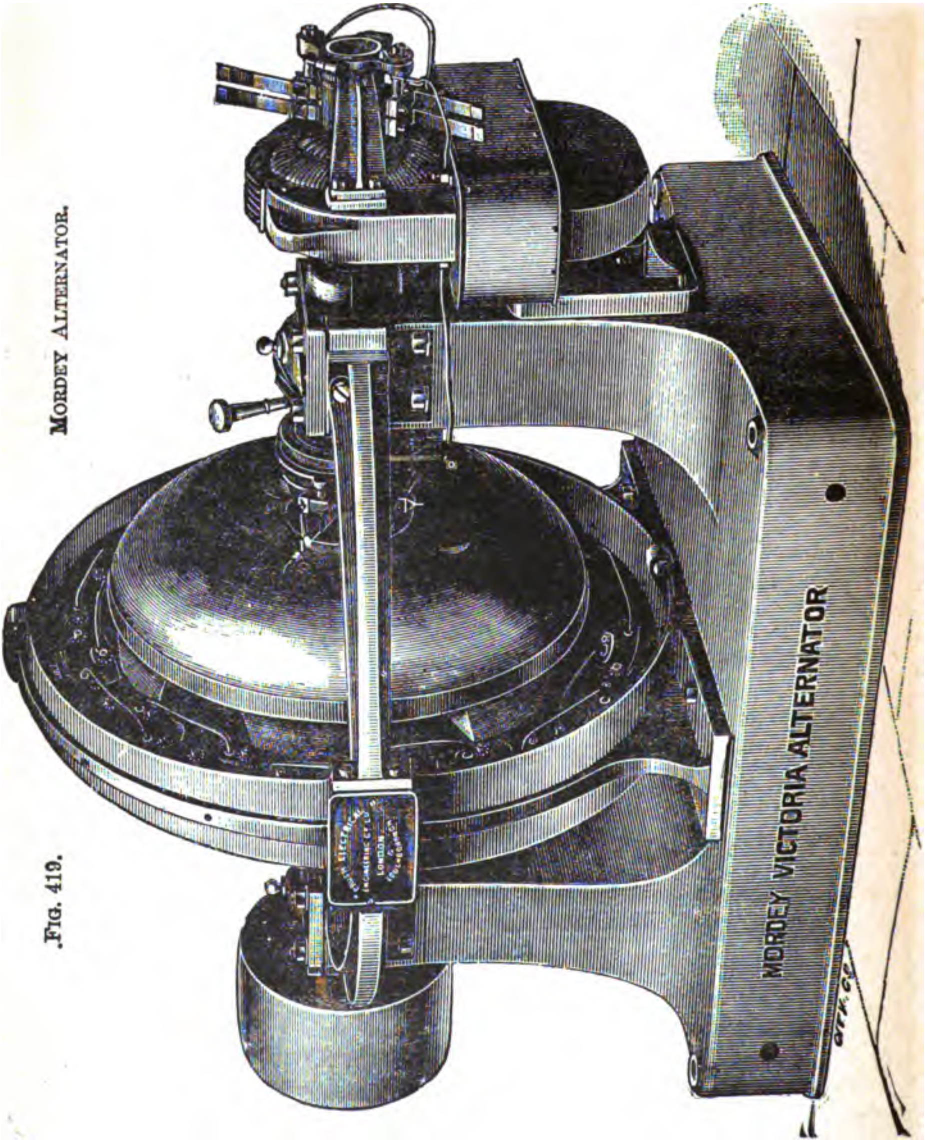

Fig. 419. Mordey Alternator.

poles between which the armature lies, all the poles on one side are of one kind, north poles, and all those on the other side are south poles. Hence there is no reversal of the magnetic field through the armature coils; the number of magnetic lines through any coil simply varying from zero to maximum and back. As a result of this arrangement, there is a great simplification of the means needed to magnetize the field-magnets. One single coil surrounding a central cylinder of iron suffices to magnetize the whole of the poles. There is indeed only one magnetic circuit, branching into separate branches. The construction of the field-magnet is as follows·—

A pulley-shaped iron cylinder, through which the shaft passes, forms the core, and is surrounded by the exciting coil. Against the ends of this core are firmly screwed up the two end castings (Plate XIV. Fig. 3) each of which is furnished with a number of polar projections varying from 9 in small machines to 60 in large ones, projecting toward one another; the narrow polar gap between them being only just wide enough to admit the armature. The entire field-magnet revolves on the shaft, the exciting coil being supplied with current from a separate machine by means of two contact rings on the shaft. There is no need for the exciting coil to revolve; but for mechanical reasons it was deemed preferable to wind it actually upon the field-magnet core. The armature coils are of copper ribbon, wound upon narrow wedge-shaped cores of enamelled slate, and insulated with a thin tape between the turns. Each coil is held in a German silver bracket embedded in ebonite and firmly clamped to the exterior frame. All the metal clampings are outside the magnetic field, and are so arranged that any one coil can be removed in a few minutes without dismounting any other part of the machine.

As the armature is stationary there are no centrifugal forces to be considered, and the coils have to be supported only with a view of resisting the tangential drag of the field. The revolving field-magnet forms an excellent fly-wheel, and as there are no parts liable to fly out, a high speed of driving presents none of the difficulties that arise with many other types of machine. The journals are furnished with a shoulder to limit end-play, and the bearing blocks are made adjustable longitudinally, so that the field-magnet may be placed exactly symmetrically with respect to the armature. The electromotive-force is 1 volt per 8½ inches of conductor. The very low resistance of the armature, and almost complete absence of armature reactions, makes the machine almost self-regulating, a point of some importance for parallel running, and for operating motors.

In some cases a small continuous-current machine is mounted on the same shaft as shown in Fig. 419, to excite the field-magnets.

Owing to the excellent conditions of ventilation, it comes about that the limit of current-density is not fixed by risk of overheating, but by considerations as to efficiency and self-regulation. The amperage at full load is no less than 3300 amperes per square inch. Loss by hysteresis there is none, owing to absence of any armature core. The eddy-currents in the conductor are trifling; the copper tape needing no further lamination. The coil-holders, moreover, are of German silver, the high specific resistance of which alloy reduces the losses by eddy-currents to $\frac{1}{16}$th or $\frac{1}{20}$th of what they would be if brass were used. A proof that the waste is almost entirely confined to the C^2r loss is afforded by the fact that a 75 kilowatt machine when driven on open circuit but excited to give its full voltage, only absorbs 3 H.P., the armature keeping quite cool. It is a curious point that in these machines the losses due to friction, hysteresis and parasitic currents, though moderately great at low loads, are not only proportionally but actually less at full load. Machines which show very great losses at low loads are uneconomical for central station work.

The construction of this alternator is more completely shown in Plate XIV., which depicts the machines erected in the Leicester central station. In its general features it is, as already seen, similar to the machines made by the Brush Company for some years, but with certain detail modifications. An end elevation, partly in section, is shown in Fig. (1); a side elevation in Fig. (2); a part section of the field-magnet—

to a larger scale—in Fig. (3); side and end views of an armature coil—to a larger scale—in Figs. (4) and (5). The armature is stationary, and consists of 120 coils mounted in ebonized German silver clamps—see Figs. (4) and (5)—secured to the armature ring by bolts passing through slotted holes in the flange of the ring—see Fig. (5). The armature coils consist of thin copper ribbon wound with suitable insulation round a slate core. Down the middle of the slate core a number of small slotted holes are drilled, these holes serving for a lacing of hard-tanned cord which is put round the coils under pressure after they have been covered with a thin layer of mica and tracing-cloth, the object of which is to prevent a sparking to the poles and to earth. They are set radially round a gun-metal ring, which is bolted to a cast-iron frame divided into four sections, two of which are below the floor level; each section is pivoted on end girders of cast iron, and can be readily swung back for inspection or repair of the coils. An equalizer is placed in one of the girders, as the two halves of the armature are connected in parallel. The field-magnet consists of massive steel castings with 60 pairs of polar projections, and is excited by one central coil provided with two gun-metal collecting rings mounted on the shaft, and the whole rotates in ample swivel bush bearings. An examination of the section of the magnet—seen in Fig. 3—will render description almost unnecessary. The field winding is an annular coil wound directly on the annular cast steel core, the winding being separated into two portions, leaving a radial space the whole way round. A number of conical radial air-passages allow a very free supply of air for ventilating and cooling purposes to pass from the hollow hub quite through the field winding, and over the armature which stands in the air-gap between the polar extensions. The magnet will be seen to consist of two cheeks secured by bolts and circular keys to the inner flanged magnet core. In smaller sizes of machines these cheeks are cast steel, each in one piece, but in the machine illustrated, and in all the larger machines, each cheek consists of two pieces, divided as shown. The armature ring is divided into four portions hinged at the ends of the machine near the horizontal diameter. This arrangement allows of any one quadrant being readily withdrawn for purposes of examination, or cleaning, or repairing. In Fig. (1) is shown a quadrant standing out from the magnet in this way. The whole of the armature coils are accessible without removing any part of the machine, because there is a gap between the adjacent poles on either side, rather more than equal to the width of one armature coil. Thus, in any position, half the armature is accessible, and by moving the field-magnet round very slightly, the other half becomes accessible. This facilitates the ordinary cleaning work, while for periodical examination it is easy to withdraw the armature quadrants as shown. End play is limited by taking the thrust on a shoulder on the shaft bearing, on the inside end of each bearing. The lubrication is effected by means of a small oil pump of the Roots' blower type, seen in Figs. (1) and (2) at the side of the machine. These machines work at 96 revolutions per minute, having an output of 100 amperes at 2000 volts. The smallness of the armature reactions may be judged by the circumstance that if the excitation is kept constant, the voltage rise from full load to no load is only 7 per cent.

A number of Mordey alternators of 750 kilowatt output were constructed by the Brush Co. for the City of London lighting station.

Mr. Mordey has designed[1] a considerable number of alternative forms, all characterized by the combination of the two principles of simplicity of magnetic circuit and non-reversal of polarity in the armature. Some designs for machines of kindred type have been patented by W. Main.[2]

Parsons' Alternator.—This is a high-speed machine of bipolar or tetrapolar type designed for running at 3000 to 10,000 revolutions per minute, when coupled to the special high-speed steam turbine[1] of the same inventor. Hence it is sometimes known as a *turbo-alternator*. This combination has lately come into notice owing to its possessing the qualities not only of a good efficiency, but of an almost complete freedom from mechanical vibrations. It has in consequence been adopted for city lighting stations in various parts of England. It occupies less space than any other form of combined plant.

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[1] Specification of Patent, 8262 of 1887.

[2] Specifications Nos. 15,858 and 16,032 of 1887. The device of employing field-magnets with a greater number of pole-pieces than of exciting coils had been previously employed by Holmes (Specification 2060 of 1868), and more recently by J. and E. Hopkinson. Another machine, by Klimenko, shown at Vienna in 1883, had a fixed armature with iron cores between the poles of a revolving field-magnet, with multiple pole-pieces.

Plate XV. gives a scale drawing of a 350 kilowatt turbo-alternator of the same design as those used by the Metropolitan Electric Supply Co. in their central station, Manchester Square, London. The armature consists of laminated iron, the core-disks measuring 18 inches outside diameter. There are 60 holes around the circumference, through 40 of which are passed conductors. Thus there are virtually only two coils, with 10 turns in each, and yet so great is the speed that a pressure of 1000 volts is generated. The machine having four poles, a speed of 3000 revolutions per minute gives a frequency of 100 per second. The governing of the machine is accomplished as follows. Steam is admitted to the turbine in a series of gusts by the periodic opening and closing of a double-beat lift-valve, the valve being opened once in every 15 revolutions. The duration of each gust is controlled by a solenoid which is connected as a shunt to the field-magnets. The field-magnets being excited by a small continuous-current machine on the same shaft as the alternator, the pressure at its terminals is a measure of the speed. The regulator, which will be seen in Plate XV. on the top of the magnets, operating a long lever reaching to the valve in question, has a series coil as well as a shunt coil, the effect of which is to increase the speed at heavy loads so as to keep the pressure constant. At full load the gusts become blended into an almost continuous blast, the lift-valve closing only momentarily or not at all. The action of this governor is most satisfactory. The consumption of steam is only 25 lbs. per kilowatt-hour at full load, and with superheating it can be still further reduced. The total weight of this plant, including turbo-alternator, exciter and bed-plate, is about 12 tons. The copper in the armature weighs 58 lbs.

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[1] See *Electrician*, xx. 103, 1887; and *Proc. Inst. Civil Engineers*, xcvii. Feb. 1889.

General Electric Co.'s Alternators.—The Thomson-Houston alternators with stationary external magnets and internal revolving armature were described in the previous edition of this work, where also an illustration was given of the "composite" method of excitation. These were high frequency machines of 133 cycles per second. Some of these alternators, of 500 kilowatt output at 100 periods per second, have recently been furnished to the City of London lighting station, where they are direct driven by Willans triple-expansion three-crank engines. The same company has lately developed a low-frequency alternator operating on an unsymmetrical 3-phase plan, termed the "monocyclic" system,[1] the third circuit being merely intended for starting motors.

Westinghouse Co.'s Alternators.—These have already been generally described. At the Chicago Exhibition in 1893 were shown some large 2-phase alternators. They resembled Fig. 402 in general design, but were virtually double machines, having side by side two similar field-magnets, each of 36 poles, and within two similar armatures upon the same shaft. But the armatures were "staggered"; that is to say, they were so mounted that one of them had an angular advance over the other equal to one-half the angular breadth from a N-pole to a S-pole. By merely shifting the second armature the same machine might be used as one single-phase alternator. In this case the adoption of a 2-phase system is not accompanied by any economy of space or material in the machine. These alternators are of 750 kilowatt output, running at 200 revolutions a minute, and having a frequency of 60 periods per second.

In its more recent polyphase machines [2] the Westinghouse Company has adopted a "distributive" winding (p. 581) of the armature. It also constructed the Niagara alternators described below (p. 636).

[1] *Electrical World*, xxv. 182; *l'Eclairage Electrique*, iii. 152.

[2] *Ib.* xxv. 713, 745, 1895.

Allgemeine Co.'s Alternators.—The *Allgemeine Elektricitäts-Gesellschaft* of Berlin has developed the 3-phase system in its alternators, from the designs of Mr. Dobrowolsky. Fig. 420 illustrates a Drehstrom generator of 89 kilowatts, with fixed external radial poles, and a revolving armature with sunk wave-winding.

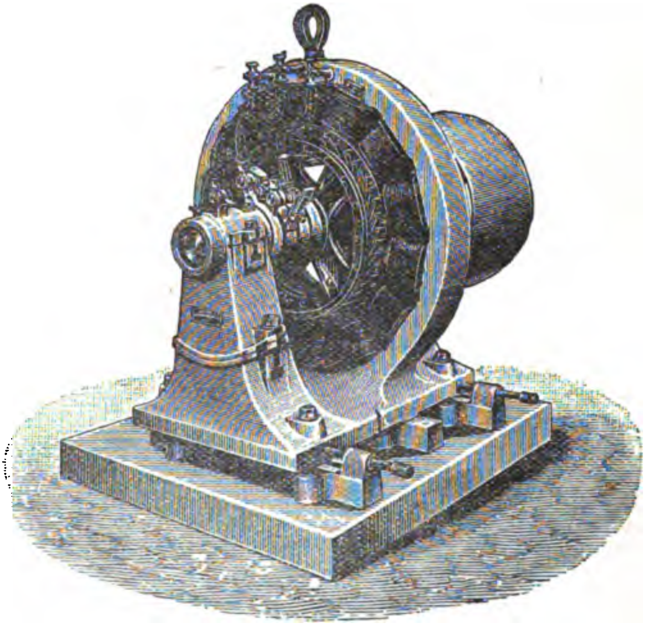

FIG. 420.—ALLGEMEINE CO.'S 3-PHASE ALTERNATOR.

The large 3-phase inductor alternators made by this company for the Strassburg lighting station are considered later.

Oerlikon Co.'s Alternators.—In 1890-91 this company constructed from the designs of Mr. C. E. L. Brown the 3-phase alternators for Lauffen on the Neckar. They were intended for supplying current to the town of Heilbronn, six miles away, but were first employed in the now famous historical transmission of power from Lauffen to Frankfort, a distance of 110 miles, on the occasion of the Frankfort Exhibition. Though propelled by vertical-shaft turbines, the alternators have horizontal axes driven by toothed wheel gearing. They have revolving internal field-magnets with an external armature with zigzag arrangements of conductors passing through holes in the core-rings. Fig. 421 gives a general view, whilst Fig. 422 shows the field-magnet after the armature has been slid away for inspection. The machine generates three currents, each of 1400 amperes at a pressure of 50 volts; taking 300 horse-power when running at 150 revolutions per minute. The armature has an external diameter of 189·4 cm. (nearly 6 feet) and an internal diameter of 176·4. The total thickness of core-rings, parallel to the shaft, is 88·0 cm. Around the inner periphery of the core-

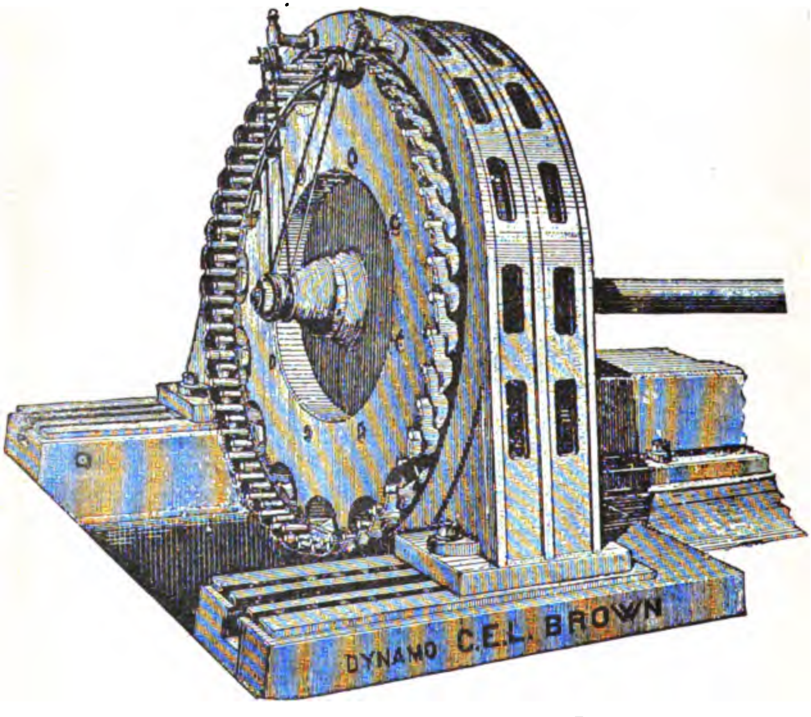

Fig. 421.—Three-phase Alternator used at Lauffen.

rings are 96 circular holes 33 mm. in diameter at distances of 60 mm. apart. Each of these holes is lined with a tube of asbestos, and through each passes a solid copper rod 29 mm. in diameter. The core-rings, built up of segmental stampings, are assembled in a strong cast-iron frame. The winding, if such it can be called, is in three independent zigzags of 32 conductors each, connected according to the following scheme :—

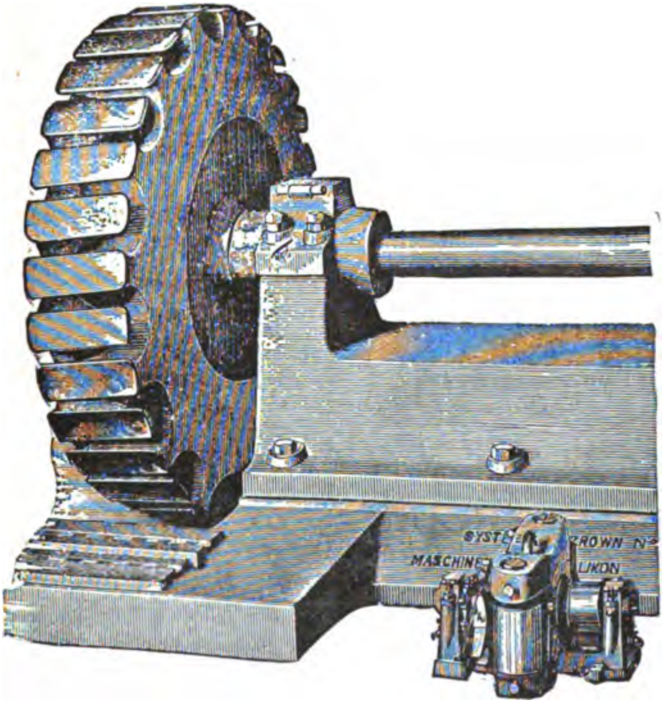

FIG. 422.—FIELD-MAGNET OF 3-PHASE ALTERNATOR AT LAUFFEN.

Set A, 1, 4, 7, 10, ... 91, 94.
Set B, 95, 92, 89, 86, . . . 5, 2.
Set C, 93, 90, 87, ... 3, 96.

The ends of Nos. 94, 2, 96, are connected to a common junction J, while Nos. 1, 95 and 93 are severally brought out to three external terminals. This constitutes a star-winding

(p. 669); the general arrangement being illustrated in Fig. 423.

The gap-space between the armature core-ring and the pole-faces of the field-magnet is 6 mm. This field-magnet has 32 poles. It is of great solidity and simplicity, having but a single magnetic circuit. The exciting coil is wound in a channel on the periphery of a sort of pulley of cast iron, to which are bolted two steel rims, each carrying 16 polar expansions or horns. Each of the polar faces has an area of 36 × 16 sq. cm. The channel is 18 cm. wide and 9 cm. deep. In it lie 496 windings of copper wire 5 mm. diameter. A section of this channel is given in Fig. 424; and Fig. 425 illustrates the way in which the polar horns project inwardly, the N-poles between the S-poles over the exciting coils. This arrangement reduces the cost of construction and of excitation to a minimum. In fact, on open circuit only 100 watts are spent on excitation—one-twentieth of one per cent. of the output; and at full load, when the armature reaction is a maximum, it is still far less than one per cent. This excitation is furnished by a small separate dynamo. The exciting current is conveyed to the rotating part by means of flexible metallic cords running over insulated pulleys, in lieu of the usual contact rings and brushes. At full speed and normal voltage,

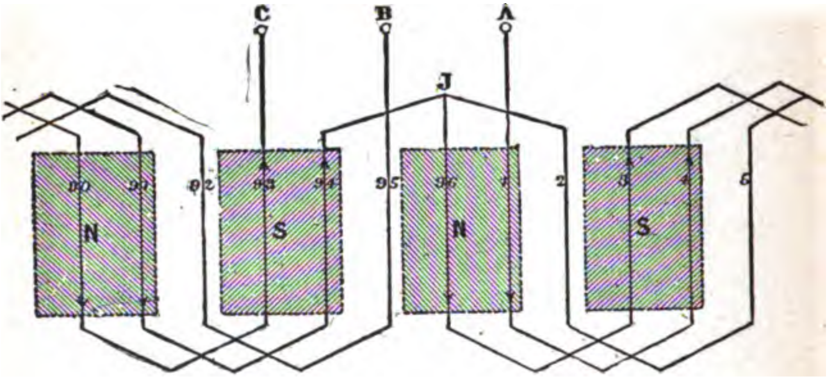

Fig. 423.—Developed Diagram of Winding of 3-phase Alternator.

the loss by friction and hysteresis is 3600 watts, or under 1·7 per cent. of the maximum output. The loss by resistance of armature windings at full load is 3500 watts, making the commercial efficiency over 95 per cent. The heating is, in the total absence of eddy-currents, quite negligible. The weight is 4¼ tons. As there are 16 pole-pairs and the speed is 150 per minute, the frequency is 40 periods per second. The electromotive-force, generated in each of the three windings, as measured between the common junction J and the outer terminal, could be increased up to 55 volts.

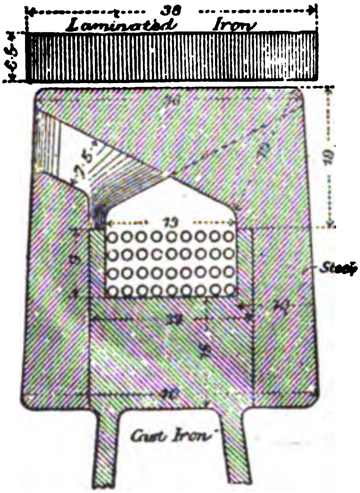

Fig. 424.—Section of Field-magnet.

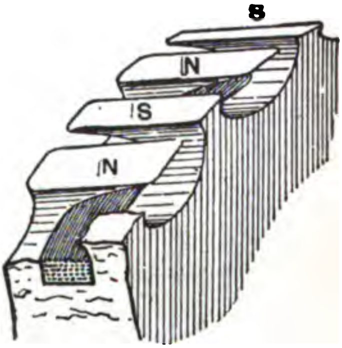

Fig. 425.—Sketch of Field-magnet.

The same design was repeated, with the difference that the shaft was set vertically over the turbines, in the three machines made by the Oerlikon Co. to convey power to their works from Hochfelden, 24 kilometres distant. They are depicted in Fig. 511.

A more recent 3-phase generator of the Oerlikon Co., shown in Fig. 426, has a revolving field-magnet of the same type as the preceding machines; but the armature is lap-wound, the coils passing through slots in the laminated external core. The exciter is carried on a bracket at the end of the machine. This machine has an output of 22 amperes at 5000 volts, at 500 revolutions per minute, taking about 150 H.P.

Brown's Alternators.—Since 1891 Mr. C. E. L. Brown has continued to develope the vertical-shaft type of generator which he introduced when constructor to the Oerlikon Co. Fig. 427 gives a general view of an alternator of the "umbrella" type, with revolving internal field-magnets, hung upon a six-armed spider. The external core-rings have perforations as in Fig. 421, through which in low-voltage machines pass the stout copper conductors coupled up in zig-zag very much as in Brown's continuous-current drum-armatures. The two-layer-winding is excellent for this type of machine. In high-voltage machines the coils are wound in a lap-winding on plans resembling Fig. 405 or Fig. 406 according to circumstances. A large number of the machines are now in operation. One of these machines, a 3-phase generator, has for some years done excellent work at Schönenwerth near Aarau in Switzerland, furnishing current for motors in a large shoe

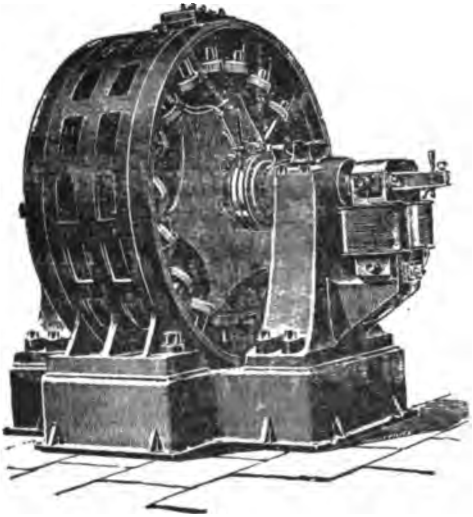

FIG. 426.—THREE-PHASE ALTERNATOR OF THE OERLIKON CO.

factory. More recently the town of Aarau has been provided with a central station which derives its power from the waters of the river Aar by means of turbines; the generators being of the same type.

To the Niagara Cataract Construction Company, Mr. Brown submitted two designs of "umbrella" type, with revolving field-magnets, for alternators of 5000 H.P. One of these designs is reproduced in Plate XVI., and shows the 2-layer winding in the stationary armature, together with the arrangements for lubrication.

In recent years various forms of polyphase alternators have been introduced by Messrs. Brown, Boveri & Co. Some of these machines present no special feature to distinguish them from ordinary alternators beyond having the coils of the armature arranged in sets of twos or threes to correspond to 2-phase or 3-phase work.

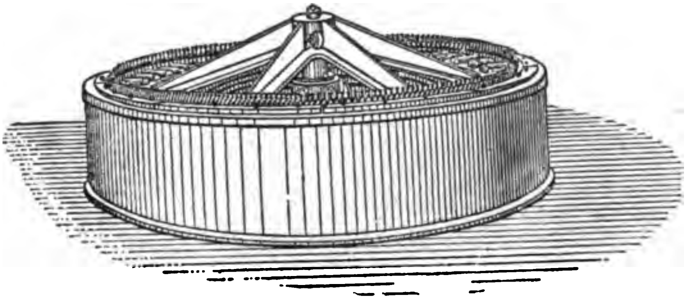

FIG. 427.—BROWN'S "UMBRELLA" TYPE OF ALTERNATOR

Recently Mr. Brown has adopted a form of revolving field-magnet having a series of outward-pointing radial poles, with the peculiarity that only alternate poles are wound with exciting coils, the intermediate ones being simply projections of cast iron of larger cross section than the intermediate cylindrical cores that receive the coils. He finds that for operating motors it is needful to employ a field-magnet less subject to armature reactions than the form used in the Lauffen alternators. Fig. 428 shows one of his 2-phase alternators of 300 H.P., in which this system of field-magnet winding is illustrated. The armature of this machine is of the same general construction as the stator of the 2-phase motor shown in Fig. 470, the only real difference between the two machines being that the one has a separately excited field-magnet, relatively to which the poles remain fixed, and the other has a rotor in which the poles change in position.

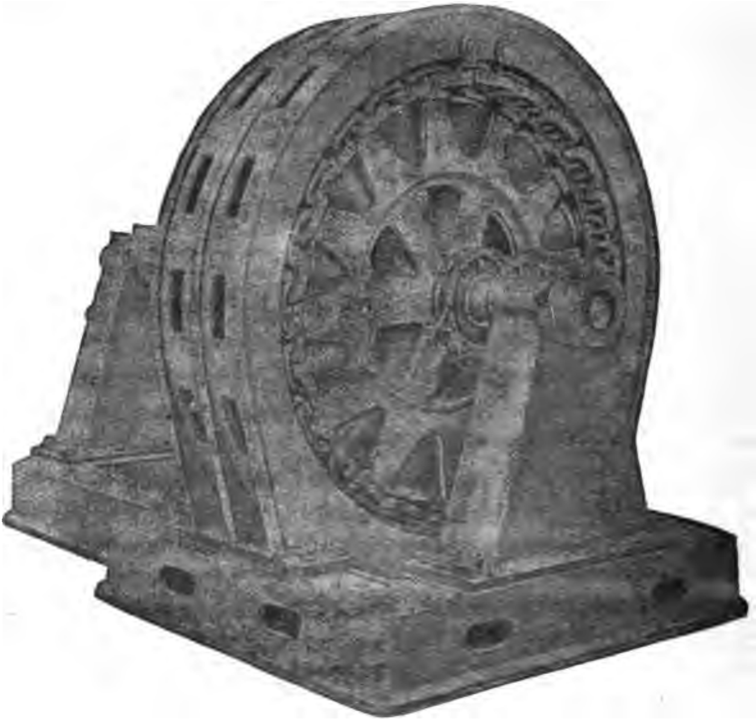

FIG. 428.—TWO-PHASE ALTERNATOR (225 KILOWATT).

For the central station at Frankfort, Mr. Brown designed the five 550 kilowatt alternators, driven at 85 revolutions per minute. In these machines (Fig. 429) the projecting poles of the revolving magnets are each separately wound, the excitation being derived from a continuous-current 4-pole machine on the end of the shaft. A point of novelty in the design is the construction of the stationary external armature as a wheel capable of being slowly turned round so as to bring each part to a position convenient for inspection and cleaning.

Plate XVII. gives the drawings of a smaller alternator of

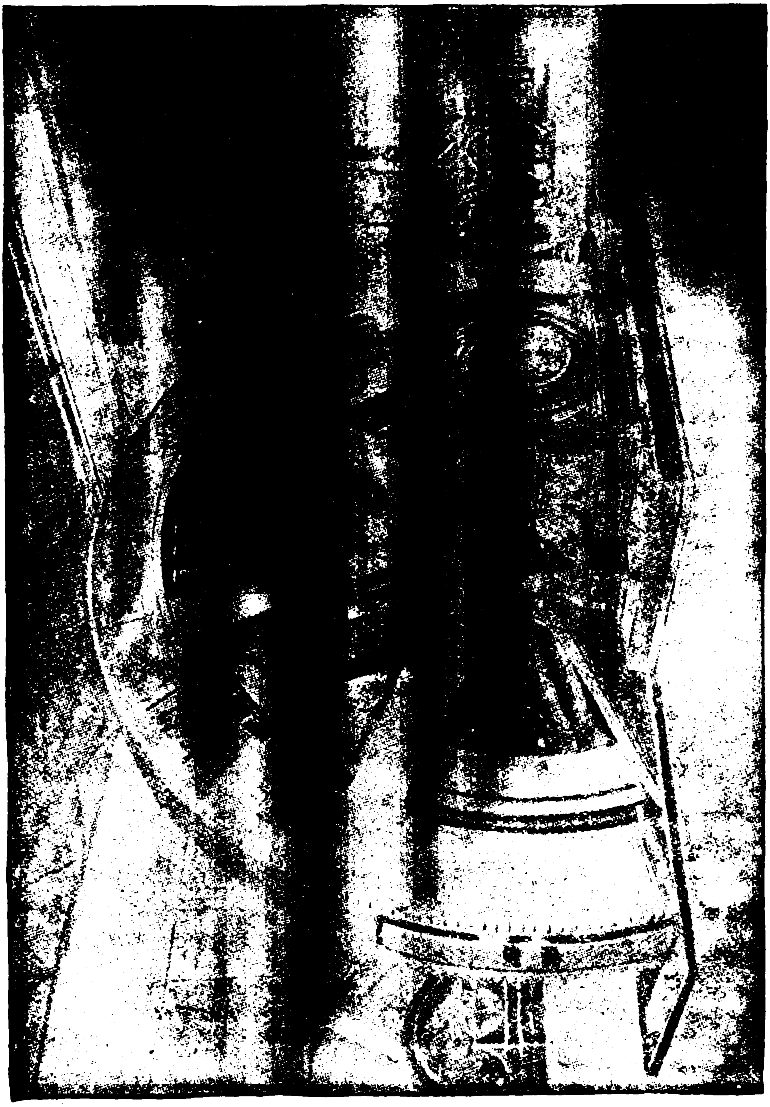

FIG. 429.—SINGLE-PHASE ALTERNATORS AT FRANKFORT.

similar design, in which can be seen the way in which the armature cores are constructed in hinged sections, allowing of being removed for cleaning or repairs.

Alioth Convertible Alternators.—Messrs. Alioth & Co. of Münchenstein near Bâle, have recently constructed several 4000 volt. 300 H.P. alternators for a power station at Neufchâtel, which are intended to be convertible at will, either into monophase or triphase machines. Fig. 430 gives a section of one of these machines parallel to the shaft, showing the exciter on the left and the detail of the self-oiling bearings. The field-magnet, as seen in Fig. 431, has nine pairs of poles and is of the same general construction as the field-magnets of the machines shown in Figs. 408 and 424. This magnet is interchangeable with one having six pairs of poles, in case the machine should be required as a 3-phaser. The crowns of poles are of mild cast steel with laminated faces. The armature coils, 18 in number, are wound on formers, and then slipped over the laminated iron projections. Connected in two sets of nine each they yield a monophase current, but when three sets of six are joined in star fashion the machine is a very efficient 3-phaser. The power station supplies both single-phase and 3-phase current, and it is convenient to have the machines convertible.

The Niagara Alternators.[1]—When the project of utilizing the water-power of Niagara by turbines was taking shape, the Cataract Construction Company invited many different manufacturers in Europe and in America to submit plans. The machines were to be of 5000 horse-power, driven by turbines making 250 revolutions per minute. Many of these designs were extremely good ; nevertheless it was determined to have the machines manufactured in America, owing to the high tariff charged on imported goods, and to the cost of transport. Some of the designs (including those of Mr. Brown) were of the " umbrella " type, but for various reasons (turning mainly upon the constructive difficulties arising from size and speed) Professor Forbes and Mr. Coleman Sellers were in-

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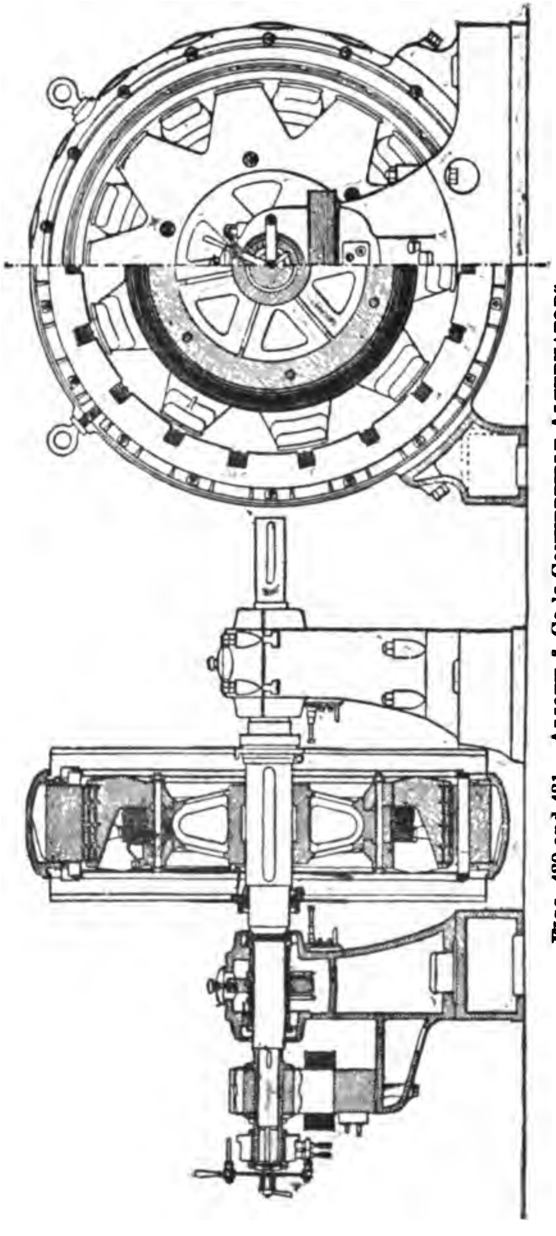
[1] For an illustrated description of the works carried out, see *Cassier's Magazine* (N.Y.), July 1895. **Figs. 432 and 433 are taken from the article by Mr. Stillwell.**



FIGS. 430 and 431.—ALIOTH & CO.'S CONVERTIBLE ALTERNATORS.

structed in May 1893 to get out further plans for alternators of the proposed type. Professor Forbes fixed upon an externally-revolving umbrella field-magnet, with inwardly-pointing poles held together by an external annulus of steel, as possessing both great strength and a large fly-wheel action.

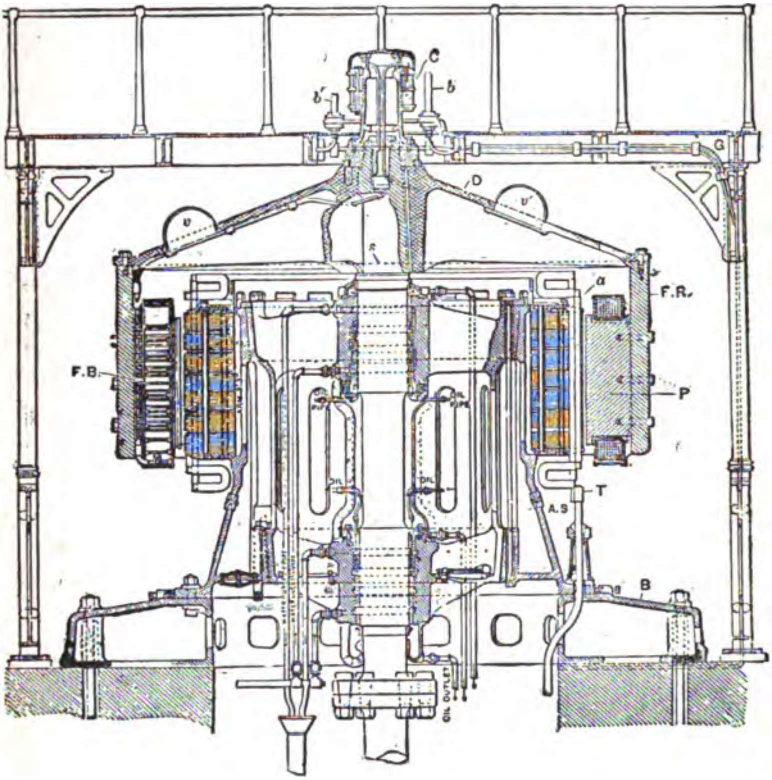


Fig. 432.—Sectional Elevation of Niagara 5000 H.P. 2-phase Generator. Scale 1 : 50.

At first he prepared designs for a 2-phase machine, having the low frequency of 16⅔ periods per second, with 8 poles. Eventually, after the Westinghouse Company had been selected as manufacturers, it was decided to fix the frequency at 25, and to wind the armatures for 2000 volts. The drawings published by Professor Forbes[1] relate to the earlier design, and have certain complications about the armature which became unnecessary when it was decided to keep the voltage at 2000.

The machines as actually constructed are shown in Figs. 432 and 433. The field-magnet consists of a nickel-steel ring

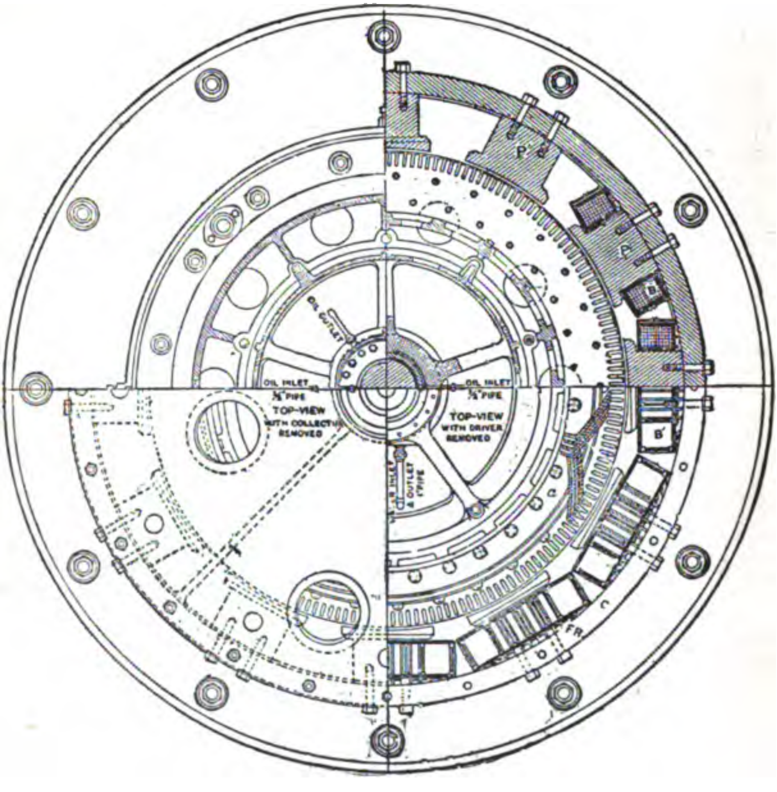


FIG. 433.—PLAN OF NIAGARA 5000 H.P. 2-PHASE GENERATOR.

forged without a weld, towards the interior of which project 12 pole-cores. This is supported by an umbrella-shaped driver fixed to the top of the shaft. There are 187 slots in the armature with two conductors in each slot. Each conductor is $1\frac{1}{32}$ inches by $\frac{7}{16}$ in section, with slightly rounded edges. The method of connecting up is seen in the drawings, as also the method of bolting the laminated iron to the cast-iron frame of the armature. Around the hub of the bearings grooves are cut (shown in dotted lines) which permit water to circulate and keep the bearings cool.

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[1] *Journal Inst. Electrical Engineers*, Nov. 1893.

CONSTANT-CURRENT ALTERNATORS.

A variety of alternators for supplying currents of an unvarying number of virtual amperes for the purpose of arc-lighting in series has been evolved in the United States; the principal forms being those of Stanley[1] and of Heisler.[2] The principle of these machines is to so construct the armature that it has great self-induction. This is accomplished in the Stanley constant-current alternator by using in the armature a fine wire of many turns wound deep in nicks in the core disks.

INDUCTOR ALTERNATORS.

In the inductor type of alternator none of the copper conductors move, the only moving parts being masses of iron whose motion sets up variations in the magnetic flux. This principle, suggested by several early workers (*see* Historical Notes, p. 11) was revived by the author of this treatise in 1883.[3] During the last two or three years much progress has been made in the application of machines of this type.

Kingdon's Inductor Alternator.—In this machine the inductor principle is applied in the following way. A ring having a large number of internally projecting poles is entirely built up of laminæ of soft iron. As shown in Fig. 434, the alternate poles A are wound with coils to serve as armature parts, whilst those between them F are wound with other coils to act as the magnet part. Upon an internal wheel are borne masses of laminated iron P, which in rotating produce rapid periodic reversals in the magnetic polarity of the cores of the armature parts, and set up alternate currents in the coils that surround them.

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[1] *Electrical World*, xv. 45, and xvi. 339, 1890; also *The Electrician*, xxiv. 623, xxv. 145, and xxvi. 20, 1890.

[2] *Electrical Review*, xxv, 207, 1889.

[3] Specification of Patents, No. 1639 of 1883, which led up to Mr. Kingdon's form, see *Electrical Review*, xxii. 178, 1888.

In the 50 kilowatt machine there are 16 field-magnet or primary coils, and 16 armature or secondary coils. The inductor wheel carries 16 inductor blocks, each just long enough to span the width of two successive coils on the poles of the outer ring. Its diameter is 4 feet 5 inches, and breadth 12 inches; speed 350 revolutions per minute.

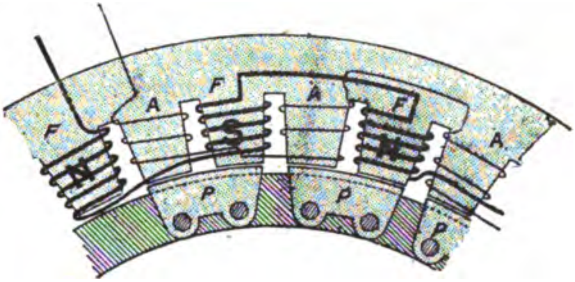

FIG. 434.—KINGDON'S INDUCTOR ALTERNATOR.

Mordey's Inductor Alternators.—In 1888, Mr. Mordey designed[1] several types of inductor machines, which were described in the previous edition of this work. In some of these machines there was but one primary winding, and in others both primary winding and secondary winding consisted of a single annular coil each, though the polar projections were numerous. These machines may be looked upon as an apparatus for periodically varying the mutual induction between two circuits in one of which there is a steady current.

Stanley-Kelly Inductor Alternators.—The Stanley-Kelly Co., of Pittsfield, Massachusetts, has brought to great perfection a 2-phase alternator, having rotating inductors of cast steel with laminated polar projections. The armature part closely resembles Fig. 477, which shows the stationary part of a Stanley-Kelly motor.

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[1] Specification of Patent, No. 5162 of 1888.

Elihu Thomson's Inductor Alternator.—This machine was described and figured in the previous edition of this work. The inductor was a simple toothed wheel, built up of laminated disks mounted on a cylinder of iron.

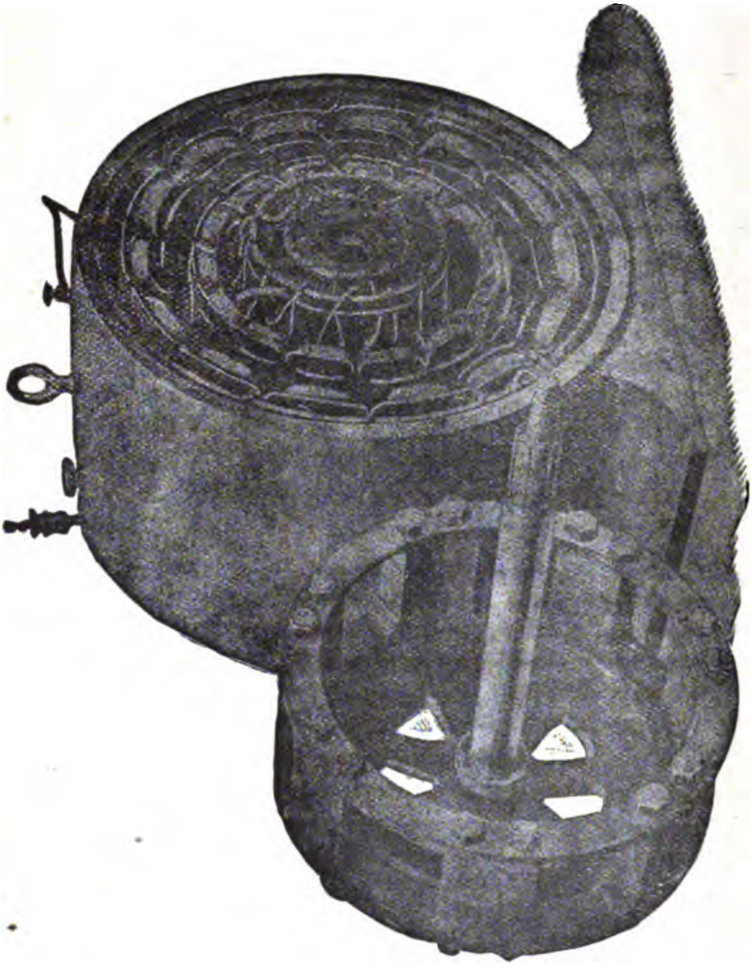

FIG. 435.—PYKE AND HARRIS'S ALTERNATOR.

Pike and Harris's Inductor Alternator.—This compact form, which has been very successful for small machines, is depicted in Fig. 435. The primary or magnetizing coil is an internal helix wound with its plane at right angles to the shaft, surrounding a central pole, and is surrounded by an external iron mantle. Two laminated rings with toothed projections support two sets of secondary or armature coils seen in the figure. On the shaft is fixed a revolving carrier which supports the laminated inductor masses. The solid part of the field-magnet acts also as a bearing. The 6-kilowatt machine runs at 740 revolutions per minute. It is 21 inches high, and weighs 350 kilogrammes.

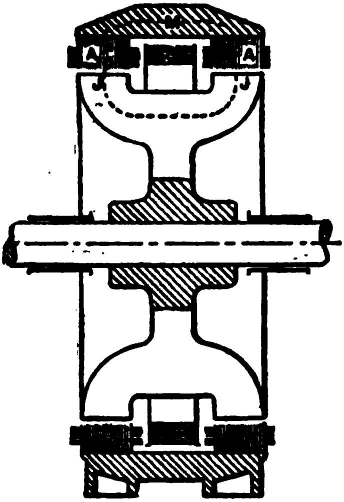

FIG. 436.—SECTION OF DOBROWOLSKY'S INDUCTOR ALTERNATOR.

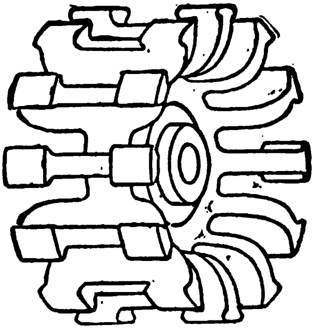

FIG. 437.—INDUCTOR OF DOBROWOLSKY'S ALTERNATOR.

Allgemeine Co.'s Inductor Alternators.—Two types of inductor machine have lately been constructed from the designs of Mr. Dobrowolsky.[1] The first, which closely resembles the Stanley-Kelly alternator, is represented in Figs. 436, 437 and 439. The magnetic circuit passes through an external iron case and two armature core-rings AA built up of stampings with teeth surrounded by coils, and is completed through the yokes J J of the revolving inductor, which is shown separately in Fig. 437. For 3-phase machines the teeth of the fixed armature part are three times as numerous as those of the inductor, as shown in Fig. 438; but pierced core rings like Fig. 406 may be used. The large 280 kilowatt alternators built by the Allgemeine Co. for the central station at

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[1] *Elektrotechnische Zeitschrift*, Feb. 7, 1895; see also *Electrician*, xxxv. 91.

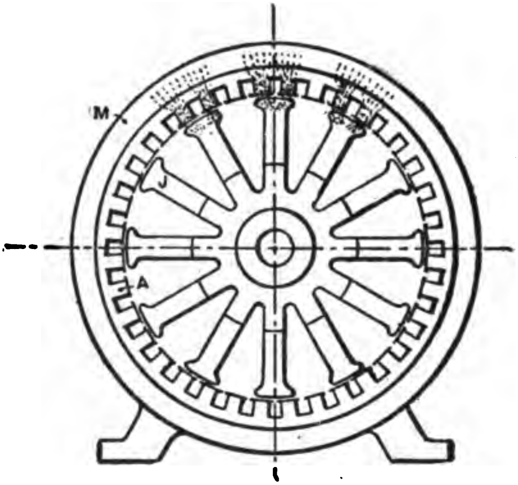

FIG. 438.—END-VIEW OF 3-PHASE INDUCTOR ALTERNATOR.

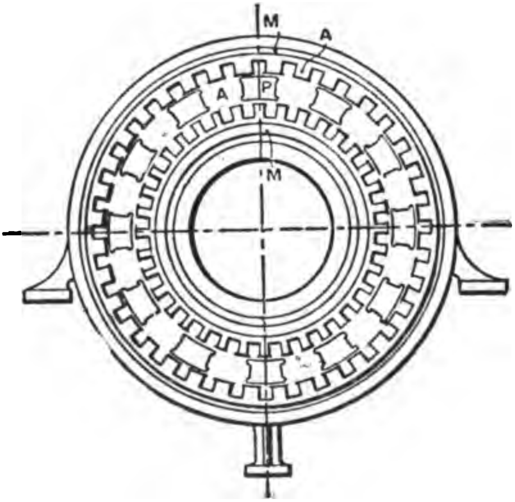

FIG. 439.—THREE-PHASE INDUCTOR ALTERNATOR AT STRASSBURG.

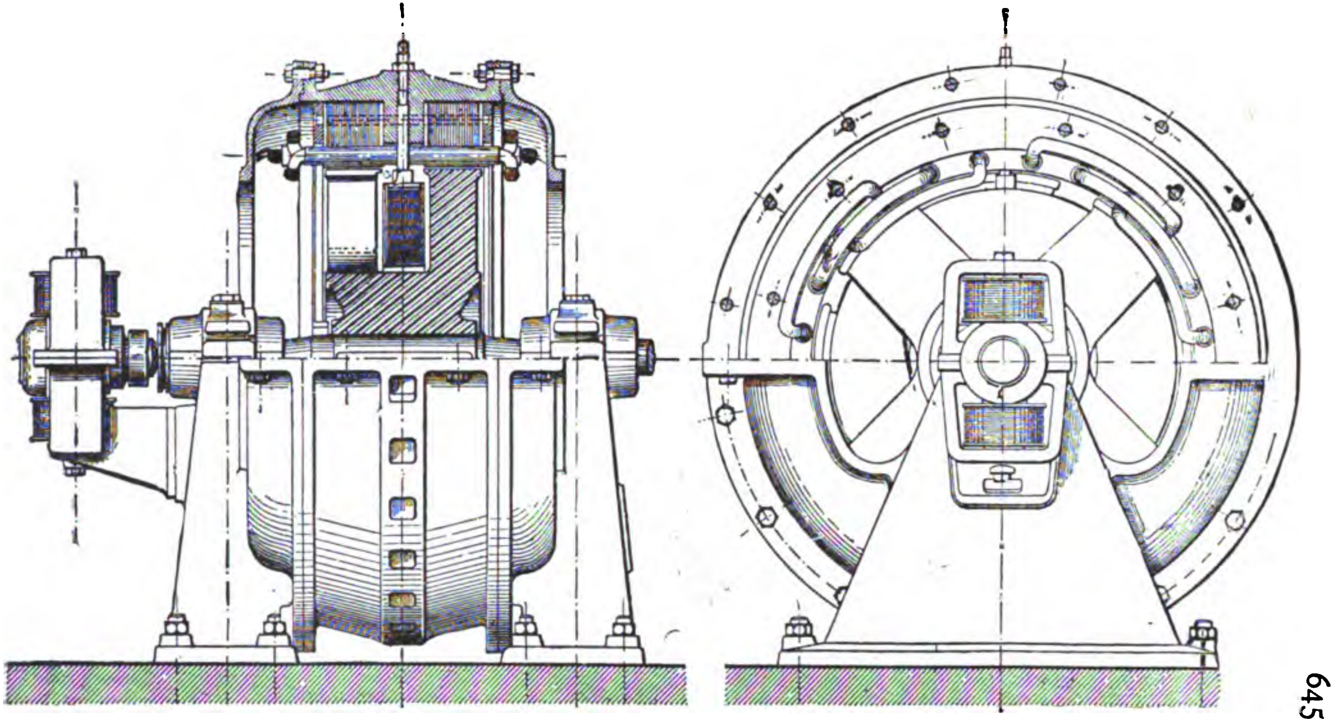

FIG. 440.—BROWN'S 3-PHASE INDUCTOR GENERATOR, 150 H.P., 689 REVS. 5300 VOLTS. Scale 1 : 20.

Strassburg, are of the same type as the Pyke and Harris machines, having laminated inductor masses P, Fig. 439, revolving between two armature core-rings. Their speed is 150 revolutions per minute. The excitation is 1·4 per cent. of the output; the armature resistance loss is 2 per cent., and total hysteresis loss is 1·3 per cent. The copper used is only 2 kilogrammes per horse-power, and the iron, excluding shaft and bearings, about 22 kilogrammes per horse-power.

Brown's 3-Phase Inductor Generator.—This is a machine constructed to meet the requirements of high speed with low frequency. The inductor magnet is simply a mass of cast steel having on each end a set of 4 arms, which, by the magnetizing action of a stationary coil between them, acquire opposite polarities. As shown in Fig. 440, these arms are set to operate alternately upon the coils of the fixed armature, which has its windings carried through holes in the inner periphery of two sets of core-disks mounted in an outer iron frame.

Other Inductor Machines.—Amongst other designs of inductor types may be mentioned those of Mr. Rankine Kennedy and M. Thury. The largest of Thury's alternators, which are built by the Compagnie de l'Industrie électrique, of Geneva, are those at Chèvres, six kilometres from Geneva, where the water-power of the Rhone is used for the lighting of that city. These machines, which are of about 900 kilowatts each, are two-phase machines with vertical shaft.

The reason of the tendency which manifests itself just now to favor the inductor type of alternator is not very apparent. Against the advantage that there is no moving copper, must be set the disadvantage of greater iron losses. In general, the efficiency of these machines is two or three per cent. lower than that of alternators of other types. They have, however, some constructional advantages in those cases where either an exceptionally high speed or an exceptionally low speed is a necessity.

CHAPTER XXIV.

THE COUPLING OF ALTERNATORS. SYNCHRONOUS MOTORS.

If two alternate-current machines are joined up in the same circuit as in Fig. 441, they are in parallel when considered as forming part of the lamp circuit, and might be both supplying current to the lamps, but they are in series with one another if we consider the alternator circuit only, for we might cut the lamp circuit out altogether and A_1 might drive A_2 as a motor. Many of the considerations which govern the running of two machines as generator and motor govern the running of two machines in parallel. We shall, therefore, up to a certain point treat the two cases together, and in doing so consider the alternator circuit only, taking a certain direction round the circuit, viz. clockwise in Fig. 441, as the positive direction of electromotive-force and current. We may as well emphasize here the importance in all alternate-current problems of clearly stating what is meant by the positive and negative sense of the quantities considered, as the utmost ambiguity and confusion arises in many important contributions to the subject owing to the neglect of this precaution.

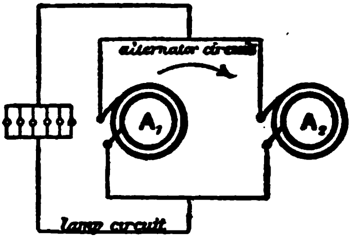

Fig. 441.

The simplest conception of two-alternate-current machines in series is that of a closed conductor *a b c d*, Fig. 442, near different points of which two magnets rotate so as to cause it to cut their lines. The part *a b* may be considered as the middle conductor of an alternator coil. The change of position of the field-magnet of an alternator with regard to the centre conductor of one of its coils is represented by the angle θ in Fig. 442. All the phase relations of the magnet's position, the electromotive-force, and the current, can be seen from this figure; and the full theory (so far as at present known) of the synchronous motor can be deduced from it by the aid of a few graphic diagrams.

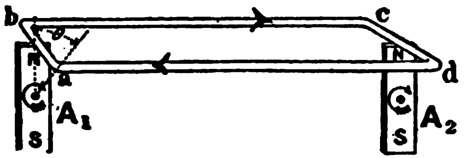

Fig. 442.

First of all consider that the magnet A_1 only is rotating. The electromotive-force e_1 induced by it, we will say, varies according to the law

$$e_1 = E_1 \cos \theta,$$

and may be represented by the projection upon a vertical line of the line $\overline{O E_1}$, drawn to scale to represent the maximum electromotive-force E_1 and which is supposed to rotate clockwise about O in Fig. 443. If the self-induction of the whole circuit is L and the resistance R, we would have from previous considerations (see p. 562) the current lagging by the angle ϕ; the vertical projection of R C at any moment representing the electromotive-force which is in phase with it. Observe that a line drawn above the axis of X represents a positive electromotive-force or current, that is, an electromotive-force or current round the circuit in the direction indicated by the big arrow-heads in Fig. 442. The alternating current flowing along *c d* would tend alternately to turn the magnet A_2 clockwise and counter-clockwise so that it would not start, but if we artificially run it up to the speed of A_1 it will, under suitable conditions, keep on running in synchronism with A_1 and exercise considerable torque. These conditions we have to consider. Let us say that at a certain instant the magnets are in the position shown in Fig. 442. The electromotive-force generated in *c d* will be negative in sense and its magnitude will depend on the strength of the magnet A_2. Suppose in the first place that the two magnets A_1 and A_2 are of the same strength, then the electromotive-force which each will induce in the circuit will be represented by the lines $\overline{O\,E_1}$ and $\overline{O\,E_2}$ in Fig. 444 ($\overline{O\,E_2}$ at the moment we are considering being negative). The two E.M.F.'s being equal and opposite, the resultant E.M.F. in the circuit will be zero, and there being no current to drive A_2 the friction of its bearings will slow it down so that it gets behind A_1 in phase. The electromotive-forces may then be represented by $\overline{O\,E_1}$ and $\overline{O\,E_2}$ in Fig. 445, and the resultant electromotive-force will be $\overline{O\,E_3}$. The phase of the current will depend upon the self-induction of the circuit. If there were no self-induction in the circuit the current would be in phase with $O\,E_3$ and its magnitude would be $\dfrac{\overline{O\,E_3}}{R}$

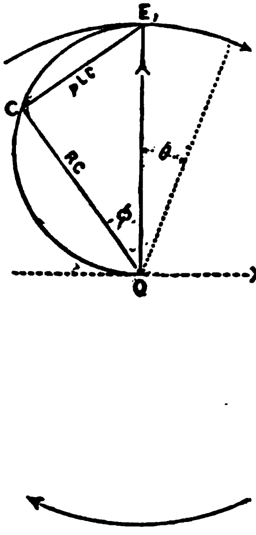

FIG. 443

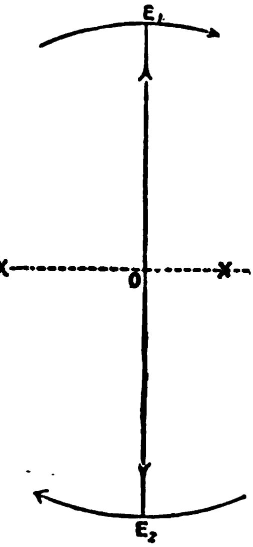

FIG. 444.

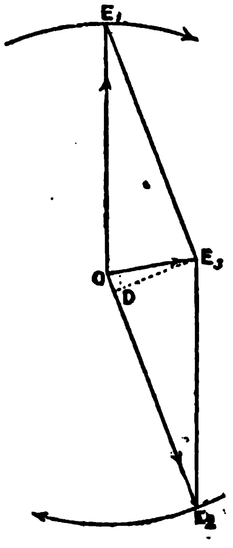

FIG. 445.

Now we have seen (p. 571) that when a current from an alternator differs in phase from the E.M.F. by less than 90°

the alternator is acting as generator and requires a force to drive it. If, on the other hand, the difference in phase between the current and E.M.F. is more than 90° (viz. between 90° and 270°) the machine acts as a motor and yields a torque. In Fig. 445 the difference in phase between $\overline{O\,E_3}$ and the electromotive-forces of both A_1 and A_2 is less than 90°, so that both machines will act as generators, and A_2 having no torque to drive it will stop. If, however, there be considerable self-induction in the circuit so that the current lags behind the resultant $\overline{O\,E_3}$ as shown in Fig. 446, where the line R C represents the phase of the current, then as the angle between it and $\overline{O\,E_2}$ is greater than a right angle, the machine A_2 will act as a motor. If we let fall the perpendicular $\overline{C\,D}$ upon the direction of $\overline{E_1\,O}$ we obtain line $\overline{O\,D}$, which divided by the resistance represents the component of the current which is in direct opposition of phase to $\overline{O\,E_2}$, that is, the part of the current which is operative in driving A_2 as a motor. The power developed by A_2 is proportional to the product

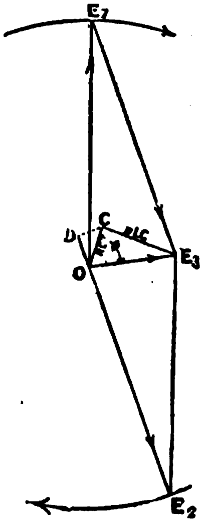

FIG 446.

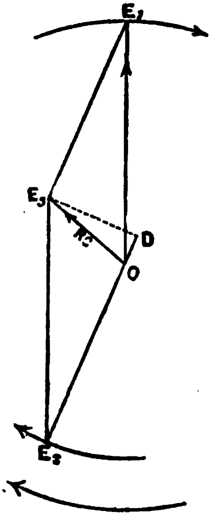

FIG. 447.

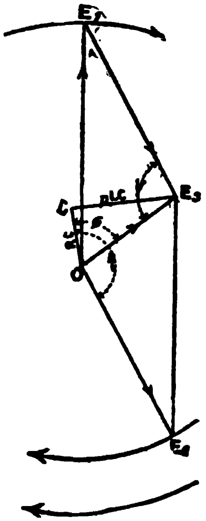

FIG. 448.

$\overline{OD} \cdot \overline{OE_2}$. As the lines in the figure represent the maximum values of the E.M.F. and current, the power is equal to $\frac{\overline{OD_2} \cdot \overline{OE}}{2R}$ (see p. 567). The magnet of A_2 would be displaced behind the magnet of A_1 just so much as to cause O D to be sufficiently great to exert the required torque.

So far we have considered the E.M.F. of the machines as equal. If we excite the magnet A_1 until it is stronger than A_2, so that E_1 is greater than E_2, then we may represent the state of affairs in Figs. 447 and 448. Fig. 447 shows what would happen if the self-induction were small as compared with the resistance.[1] The resultant E_3, and therefore the current, is more than 90° out of phase with E_2, a great torque results which makes the magnet of A_2 go faster than A_1 until it gets just so far in advance of it that $\overline{OD}$ is diminished to an amount which will give the required torque and no more. Thus we see that the effect of having the motor under-excited is to make its magnet lead in phase, while the effect of self-induction is to make it lag. If there is considerable self-induction in the circuit (as is usually the case, particularly with alternators with iron in the armatures), the phase relations of the various E.M.F.'s are those shown in Fig. 448. This may be taken as representing the most usual case of transmission of power by means of a synchronous motor; the effect of the self-induction in the circuit is to enable the motor to yield considerable torque whether its magnet is under or over-excited. Let us consider more exactly what happens when the excitation of field-magnet of the motor is varied, the load on the motor remaining constant. We see from Fig. 448 that $\overline{OE_2} = \overline{E_1E_3}$, so that we may take $\overline{E_1E_3}$ to represent the E.M.F. of the motor, that is to say, the counter E.M.F. or "back" E.M.F., as it is usually called. We may then draw the half-figure on a larger scale (see Fig 449), and consider what happens when $\overline{E_1E_3}$ is varied in magnitude, while the impressed volts $\overline{OE_1}$, the resistance R, the self-induction L, and the power of the motor P, all remain constant. R and L being known, ϕ, the angle of lag of the current behind the resultant E.M.F. $\overline{O\,E_3}$ is ascertained $\left(\text{for } \tan\phi = \frac{p\,L}{R}\right)$ and remains constant. Produce $\overline{O\,C}$ to F, and upon $\overline{O\,E_1}$, as diameter, describe the circle E_1 F O having the centre G. Join $\overline{F\,E_1}$ then E_1 F O being a right angle, $\overline{O\,F}$ is the projection of the impressed volts $\overline{O\,E_1}$ upon the direction of the current $\overline{O\,C}$, so that $\frac{\overline{O\,F}}{\sqrt{2}}$ gives the value of the virtual volts which are in phase with the current, whose virtual value is $\frac{\overline{C\,O}}{\sqrt{2}\,R}$. The power yielded by the generator A_1 is therefore $\frac{\overline{O\,F}\,.\,\overline{C\,O}}{2\,R}$. Similarly $\overline{F\,C}$ being the projection of $\overline{E_1\,E_2}$, the power yielded by the motor A_2 is $\frac{\overline{F\,C}\,.\,\overline{C\,O}}{2\,R}$, and this we are taking as constant. Now when the line $\overline{E_1\,E_3}$ alters in length the figure becomes changed in shape, but always in such a manner that the angle E_1 F O remains a right angle, so that F moves on the circle E_1 F O. At the same time the point C must move[1] on a circle C J H concentric with circle E_1 F O, in order that F C . C O (or J O . C O) may remain constant. Now, if C moves on the circle C J H the point E_3 must also move on a

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[1] See Bedell and Ryan, "Action of a Single-phase Synchronous Motor," *Amer. Inst. Electr. Eng.*, March 1895, p. 197.

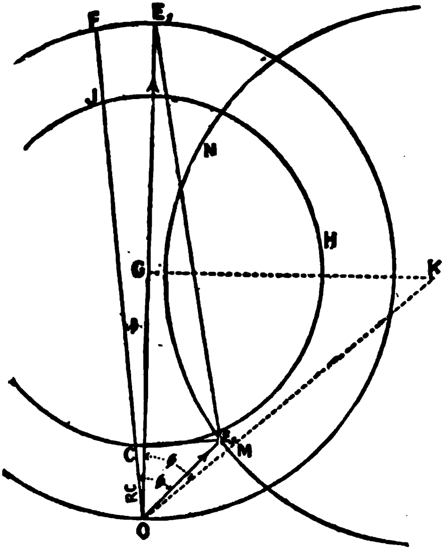

FIG. 449.

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[1] R. V. Picou, "Transmission de Force par Moteurs alternatifs synchrones," *Bull. Soc. Int. Electriciens*, Feb. 1895.

circle, because ϕ remains constant and $\overline{OC}$ and $\overline{OE_3}$ bear to each other a constant ratio. The centre of the circle M E_3 N which forms the locus of E_3, will be found by drawing $\overline{OK}$, making the angle ϕ with $\overline{E_1 O}$ and drawing $\overline{GK}$ at right angles to $\overline{E_1 O}$. We are now able to find the value of any of the quantities represented in the figure for any given value of $\overline{E_1 E_3}$, the back E.M.F. of the motor. It may be pointed out that though $\overline{OE_1}$ has been taken to represent the electromotive-force induced in the conductors of the generator, all the above clock diagrams are equally applicable to the case where $\overline{OE_1}$ represents the electromotive-force of the line at the terminals of the motor; but then R and L represent the resistance and self-induction of the motor only. We see that in the figure as drawn the current lags behind the impressed volts $\overline{E_1 O}$ by the angle β. If we decrease $\overline{E_1 E_3}$ we see that β will increase and R C will also increase. That is to say, if we decrease the excitation of the motor, the lag of the current behind the impressed volts increases and the current increases. If, on the other hand, we increase the excitation, we see from the figure that as E_3 moves up to M the angle β decreases to zero, the current being then at a minimum.[1] A further increase of the back E.M.F. of the motor will cause the current to increase, but instead of lagging behind the impressed volts it leads, the motor in fact acting as though it were a condenser placed in the circuit. If we plot a curve with the values of the back E.M.F. of the motor (or the exciting current when that is proportional), as abscissæ and the armature current as ordinates, we get a V-shaped curve showing the decrease of the armature current to a certain minimum, and its increase again as the back E.M.F. is augmented.

Mr. Mordey[2] obtained from a 50 kilowatt alternator running as an unloaded motor, the curve shown in Fig. 450. The values of the current in the motor field-magnet are taken as abscissæ, and the current in the armatures as ordinates.

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[1] Blondel, "Couplages et Synchronisation des Alternateurs," *La Lumière Électrique*, 1892, xlv. 423–563.

[2] "On Testing and Working of Alternators," *Inst. Elec. Engs.*, Feb. 1893.

Messrs. Bedell and Ryan[1] have given a similar curve for a small Westinghouse alternator, together with full particulars as to the E.M.F.'s of generator and motor and angles of lag, and have worked out clock diagrams for different points on the curve, showing that the theory agrees with what is found to occur in practice.

This property of an over-excited synchronous motor of causing the current to be in advance of the impressed E.M.F. would enable such machines to be used to counteract the tendency of the current to lag when transformers are in circuit, and thus to increase the power-factor of the line.

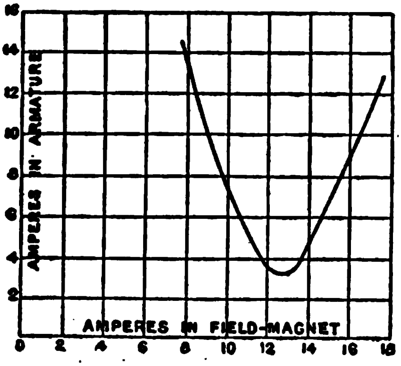

FIG. 450

One of the bad effects produced by a current lagging behind the E.M.F. of the generator, is the demagnetizing action of such a current upon the field-magnet (see p. 596). It will be seen from Fig. 442 that so long as the current is in phase with the volts it has no demagnetizing effect, for when the current is at its maximum the magnet pole is directly in front of the conductor, as in A_1 in Fig. 442. An instant before the pole comes to this position, the armature current is helping the magnetizing current, and an instant afterwards it is opposing it, so upon the whole the mean strength of the magnet is not affected, though the maximum E.M.F. in the armature probably occurs a little sooner than it otherwise would do. If, however, the current lags, the maximum current flows just after the pole has passed the middle position, thus producing a strong demagnetizing action and a consequent fall in the volts unless the excitation of the field-magnets is augmented. If, however, the current leads, the maximum occurs when the pole is approaching the conductor, increasing the magnetization, and thus the volts are raised. A generator and motor being in opposition of phase, a current that lags with regard to the one leads with regard to the other; thus on switching in an under-excited synchronous motor to a generator whose current lags, there is a tendency for the generator volts to fall and the motor volts to rise. On gradually increasing the excitation of the motor the generator volts will rise, owing to the advance of the phase of the current. This is very clearly shown in the paper of Messrs. Bedell and Ryan before referred to (p. 654).

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[1] "Action of a single-phase Synchronous Motor,' *Journal of the Franklin Institute*, March, 1895.

R. V. Picou has pointed out that in applying the construction given in Fig. 449 to the working out of a practical case, the lines $\overline{O E_1}$ and $\overline{E_1 E_3}$ representing several thousand volts are so great, relatively to $\overline{O E_3}$, that the arcs of the circles E_1 F O and C H J may be considered as straight lines, and $\overline{O E_1}$ and $\overline{E_1 E_3}$ as parallel. The construction is then simplified, and there is no difficulty in working to scale. An example is worked out in M. Picou's paper referred to above (p. 652).

There are several interesting deductions to be made from the graphic construction given above. Obviously the most economic condition for ordinary power transmission is to have the excitation of the motor such that the current is in phase with the impressed volts. Referring to Fig. 449, let us fix the condition that R C shall be in line with $\overline{O E_1}$ and draw our diagram as in Fig. 451, setting off the line O Z, making the angle ϕ with $\overline{E_1 O}$. For any given load on the motor there is one particular value of current which will satisfy the prescribed

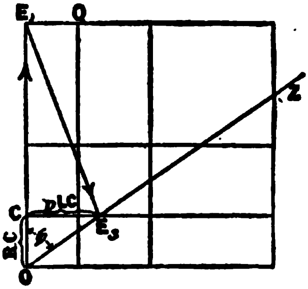

FIG 451.

condition, and the line $\overline{C\,O}$ which represents R C will have to be set off at such a length, that $\frac{\overline{E\,C}\,.\,\overline{C\,O}}{2\,R}$ is equal to the given power (see p. 652). Then drawing $\overline{C\,E_3}$ at right angles to cut $\overline{O\,Z}$, $\overline{E_1\,E_3}$ will represent the back E.M.F. of the motor in magnitude and phase. Now if we vary the power C will move along $\overline{O\,E_1}$ and E_3 will move along $\overline{O\,Z}$, the power yielded by the motor being always equal to the area of the rectangle C Q divided by 2 R, and that supplied by the generator equal to the area of the rectangle O Q divided by 2 R. When the power is zero $\overline{E_1\,E_3} = \overline{E_1\,O}$, the current being zero. The maximum power occurs when C Q is a square. From the figure we see that then

$$\text{max. power} = \frac{E_1^2}{4\,R},$$

R C being equal to $\frac{1}{2}$ E_1 and the efficiency being 50 per cent. Thus we see Jacobi's law of the continuous-current motor, and the construction given on p. 496, are equally applicable to the alternate-current synchronous motor. The back E.M.F. of the motor for any prescribed power can be found readily from the figure (see p. 655, line 20).

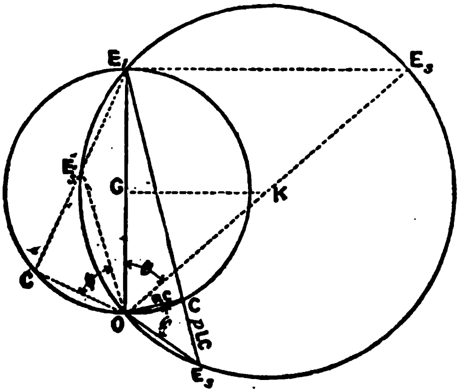

Fig 452.

We can also get a very simple figure by which to study the changes in the back E.M.F. and current when the power is zero. The clock diagram for this case is given in Fig. 452, where R C is at right angles to $E_1\,E_3$, because if the power is zero the current must be at right angles in phase to the back E.M.F. of the motor. As we change the value of $E_1 E_3$, the locus of the point C must therefore be the circle O C E_1; and from the reasoning on p. 652, the locus of E_3 must also be a circle whose centre is at K.

If we plot a curve taking on a convenient scale the back E.M.F. as abscissæ and the armature current as ordinates we find it is in the form shown by the thick line in Fig. 453. Beginning with E_3 coinciding with O we get the corner point C_0 in Fig. 453. As we increase the back E.M.F. passing counter-clockwise round the circle O E_3 E_1 in Fig. 452, the current increases until we reach the point E'_3 when it attains its maximum. R C is then equal to E_1, therefore the current $C = \frac{E_1}{R}$. If the motor were standing at rest the current through the armature would only be $\frac{E_1}{\text{impedance}}$, but if the motor is running light the back E.M.F. might be so adjusted in magnitude and phase as to completely balance the self-induction of the armature, so that a current would flow through it equal to $\frac{E_1}{R}$. In practice the upper portions of the curve in Fig. 453 would be difficult to realize unless the motor were constrained to keep in the proper phase relations, but theoretically we can follow E_3 round its circle until it coincides with E_1.

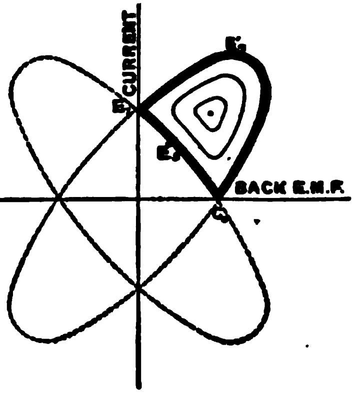

FIG. 453.

This curve C_0 E'_3 E_1 in Fig. 453, really forms part of an ellipse shown in dotted line, the equation to which is given below. If we follow E_3 further round its circle in Fig. 452 we find it passes through the point E_1; a question then arises as to whether we will give the positive or negative sign to the back E.M.F. in plotting the curve in Fig. 453.

The back E.M.F. having passed through zero would theoretically be negative, which would take us along the dotted ellipse, but if we still choose to call our back E.M.F. positive then our curve is the thick line $E_1 C_0$. This forms part of another ellipse similar to the first, that lies with its major axis sloping the other way as shown in the figure. If instead of plotting the back E.M.F. and current from Fig. 452, where the power is zero, we plot them from a clock diagram like that in Fig. 449, where the power has a fixed value, we would get curves like those shown by the fine lines in Fig. 453, the area enclosed by the curve becoming smaller and smaller as the power is increased, until at maximum power there is only one point representing current $= \frac{E_1}{2R}$ and back E.M.F. $= \frac{E_1 \sqrt{R^2 + p^2 L^2}}{2R}$. It is the lower corners of these curves that form the V-shaped curves referred to on p. 654. The equation to these curves is very simply deduced; for remembering that, in Fig. 448, the lines $\overline{OE_1}$, $\overline{E_1 E_3}$, $\overline{OE_3}$ represent respectively the electromotive-forces E_1, E_2 and IC, where I, the impedance, $= \sqrt{R^2 + p^2 L^2}$ we have

$$E_1^2 = E_2^2 + I^2 C^2 + 2\, E_1 \,.\, I C \,.\, \cos \psi \qquad (1)$$

and $\cos \psi = \cos(\phi - \eta) = \cos \phi \cos \eta + \sin \phi \sin \eta$. Further we know

$$\cos \phi = \frac{R}{I}, \qquad \sin \phi = \frac{p\,L}{I};$$

$$\cos \eta = \frac{P}{E_2 C}, \qquad \sin \eta = \sqrt{1 - \left(\frac{P}{E_2 C}\right)^2},$$

where P = power of motor.

Substituting these values in (1) we get

$$E_1^2 - E_2^2 - I^2 C^2 - 2 R P = 2 p L \sqrt{C^2 E_2^2 - P^2},$$

which is the fundamental equation of the synchronous motor.[1] Taking E_2 and C as the only variables we obtain a curve like those in Fig. 453 for each value of P.

PARALLEL RUNNING OF ALTERNATORS.

It is found very convenient in central lighting stations to be able to run alternators in parallel, so that the machines may feed into one set of omnibus bars, and their number be altered at will to suit the load on the station, instead of assigning different parts of the town circuits to separate machines.

The principles which govern parallel running have been considered in Fig. 446. $\overline{OE_1}$ may be taken to represent the volts between the omnibus bars. The machine to be thrown in in parallel is run up to speed and its excitation is adjusted until its volts $\overline{OE_2}$ are equal to $\overline{OE_1}$. It has, before being switched in, to be *synchronized*, that is to say, it must not only be run at the same speed but the impulses of its electromotive-force must be got into step with those of the omnibus bars. To do this a synchronizer is employed. Fig. 454 illustrates the principle of one form of synchronizer. An incandescent lamp is fed from two transformers in series with one another: the primary of one transformer is connected with the omnibus bars, and that of the other to the alternator to be synchronized. The connections are so made that when the machines are in synchronism the secondaries of the transformers assist each other in lighting the lamp. When not in synchronism they are in opposition. If the alternator to be thrown in is not going at the right speed it gets into and out of step alternately and the lamp blinks rapidly. The supply of steam is then altered to correct the speed, and the lamp is seen to blink more and more slowly until it takes several seconds between the instant of perfect darkness and the instant of full incandescence.

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[1] Steinmetz, "Theory of the Synchronous Motor," *Amer. Inst. Elec. Engs.*, Oct. 1894; Rhodes, "A Theory of the Synchronous Motor," *Proc. Physical Soc.*, April 26, 1895, *Phil. Mag.*, July 1895. Also "Alternate Current Motors," *Elec. Review*, 1895, xxxvii. 182, 222.

Just at the moment of full incandescence, and when the voltmeter (see Fig. 454) indicates the full pressure, the switches are closed and the lamp forthwith shines without fluctuation, showing that the volts of machine are in step with the volts of omnibus bars. If the supply of steam is now increased the alternator will take up a portion of the load. The amount of current it will supply depends entirely on the amount of steam admitted to drive it. If the steam were cut off it would run as a motor and drive the engine. Fig. 446 does not show the main current supplied to the outside circuit, it only shows the resultant electromotive force $\overline{OE_3}$ round the alternator circuit (see Fig. 441) which comes into existence in case A_2 should lag a little. This resultant electromotive-force produces a current which by reason of the self-induction of the circuit is out of phase by more than 90° with the lagging machine, and which therefore supplies power to it and hurries it up. It will be seen from the figure that the current represented by O D is greatest (for a given lag of the machine) when the angle ϕ is 45 degrees; that is to say, when in the alternator circuit R is equal to p L. In well-designed machines R and L are both kept as small as possible. It is sufficient if R is something of the order of p L.

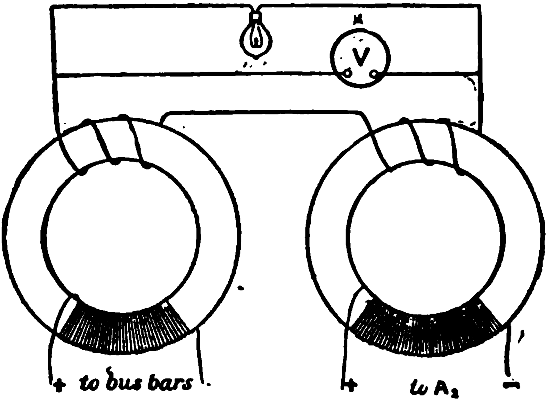

FIG. 454.

Synchronous Polyphase Motors.—A polyphase system of distribution, while giving great facility in the use of self-starting motors, does not sacrifice the possibility of installing synchronous motors in cases where perfect uniformity of speed is desired. A synchronous motor for a polyphase system may consist of an ordinary alternator placed across two of the mains; but preferably it is identical in construction to the polyphase generators, and connected to all the lines. It differs from an asynchronous motor mainly in the fact that instead of a rotor (Fig. 460) it has a field-magnet separately excited by means of a continuous current; and as the poles always keep the same position relatively to the iron of the magnet when once they are run up to the speed of the revolving poles of the armature, the respective poles take hold of each other and the magnet is dragged round in perfect synchronism. The ordinary single-phase synchronous motor, as we have seen, must be run up to speed by some independent source of power; but in a polyphase system the rotatory field acting upon conductors sunk in the pole pieces of field-magnets is sufficient to start the motor. It is thus possible to so far combine the principle of a polyphase asynchronous motor with a truly synchronous motor, that it shall be capable of starting itself, and after running up to speed, will keep its speed at all loads as constant as the periodicity of the supply. It is to be noted that while a polyphase generator will always act as a synchronous motor, it is not necessarily self-starting. Its design should facilitate the generation of currents in the polar projections if it is intended to be self-starting. A very good instance of an installation of synchronous motors of this kind is at the Ponemah Cotton Mills, Taftville, Conn., U.S.A.[1] Six hundred horse-power is transmitted, at a pressure of 2500 volts, from a mill three miles distant, where water power is available. The system is a three-phase one. The motors are the same in construction as the generators, and while being able to start themselves, run under load with perfect synchronism. The efficiency of the complete transmission from the power applied to the dynamo pulley to that delivered to the motor pulley is reported to be 80 per cent.

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[1] *Elec. Review*, (N.Y.), 1894, xxiv. 210; and see *ibid.*, 1895, xxvii. 82.

CHAPTER XXV.

ASYNCHRONOUS MOTORS.

MOTORS in which the rotation is produced by the induction of currents as the field shifts around, present the structural advantage that they can be made without commutator, and even without sliding contacts of any kind. The induction of these currents in an entirely detached structure depends upon the circumstance that the running is *asynchronous:* that is to say, that the revolutions made by the moving part do not correspond to the periodicity of the impressed currents.

Asynchronous motors may be grouped under two heads: (i.) *polyphase;* (ii.) *monophase.* In the former two or more alternate currents of equal period, but differing in phase, are employed to produce, as explained below, a *rotatory magnetic field;* this rotatory field tending to set up induced currents in all conducting masses placed within them, and by the reaction of these currents to rotate these masses mechanically. In the monophase class a simple oscillatory field is impressed by an alternate current, and this acting on a revolving system of conductors is, by the action of the induced currents, converted into a rotatory field with effective driving power.

As the subject has lately been treated *in extenso* in the author's work on 'Polyphase Electric Currents and Alternate-Current Motors,' the present chapter may be brief.

Production of a rotatory Magnetic Field.—If an alternate current is led around a coil it produces along the axis of the coil an alternating or oscillating magnetic field. If there is an iron core the magnetic flux in it will be an alternating flux; that is to say, one that begins, increases to a maximum along a fixed direction, dies away, reverses along the direction and increases to a negative maximum, and dies away to begin the cycle over again. The frequency of this alternating flux will be the same as that of the current. We have to show that by combining two or more alternating magnetic fields that are in different directions and in different phases we can produce the same effect as a magnetic field of constant intensity rotating in direction.

It is well known that a uniform circular motion can be decomposed into two rectilinear harmonic motions at right angles to one another, the two having equal amplitude, equal period and a phase difference of one-quarter period. Let P be a point uniformly revolving around centre O (Fig. 455); let the angle X O P $= \theta$. The projections of the radius O P upon the two axes are O M and O N. If the radius O P be called r we have O N $= r \sin\theta$, and O M $= r \cos\theta = r \sin (\theta + 90°)$. While P revolves the point N will oscillate up and down the line Y Y′; the amplitude of its motion being equal to the radius of the circle. Also the point M will oscillate along the line X X′ with equal amplitude and in equal time; but O N will be at its maximum when O M has zero value, and *vice versâ*. It follows kinematically that a uniform circular motion may be produced out of two straight-line motions, by combining them at right angles, provided they are harmonic, of equal period, of equal amplitude and differing by an exact quarter period.

Mechanically this motion is equivalent to that of two pistons having equal travel, working by two connecting rods upon the same crank pin, but placed at right angles to one another (Fig. 456). If the cylinders are made to produce two rectilinear motions one ahead of the other by a quarter period in time, the apparatus will combine these motions into a true circular motion. If the two cylinders are set parallel side by side two cranks will be needed, one at right angles to the other.

A similar combination can be[1] magnetically effected. If an alternating current is led round a coil so as to produce an alternating or oscillating magnetic field along the line O X, and a second alternating current is led round a second coil so as to produce a second alternating magnetic field along the line O Y, then the result will be a *rotatory* magnetic field, provided these two magnetic fields are of equal period and amplitude, and differ exactly a quarter in phase. If they are of equal period, but not of exactly equal amplitude, the result will be equivalent to an *elliptically*-rotating magnetic field; that is to say, one in which the strength and direction of the field is represented by the successive values of the radius vector drawn to an ellipse from its central point. An elliptically rotatory field will also be produced if the two component magnetic fields, though equal in period and amplitude, do not differ by exactly a quarter period. For a perfect rotatory field, corresponding to uniform circular motion, the two components must vary precisely as the sine and the cosine[1] of an angle respectively. The two-phase system of currents for producing a rotatory magnetic field is the electrical analogue of the two-crank mechanism.

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[1] See Marcel Deprez, *Comptes Rendus*, ii. 1193, 1883.

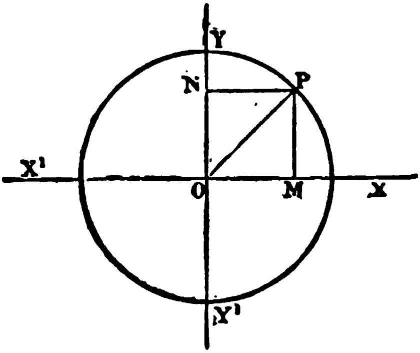

FIG. 455.—DEPREZ'S THEOREM.

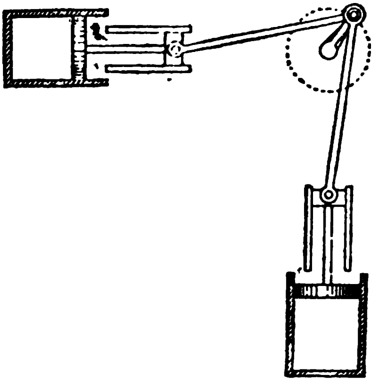

FIG. 456.—TWO-CYLINDER ENGINE.

This is not by any means the only combination that will produce a rotatory magnetic field. The mechanical analogues of the three-crank engine, and of the three-throw pump, at once suggest other solutions. In the former instance three cylinders are used, with three pistons which operate in successive phases differing by one-third of a period from one another.

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[1] See also Ferraris, "Rotazioni elettrodynamiche," *Turin. Acad.*, March. 1888.

If the three cylinders are set (as in a Brotherhood's engine) at 120° to each other (Fig. 457) their connecting-rods may actuate a single crank. If the three cylinders are set parallel side by side, then there must be three cranks spaced out in angular positions 120° from one another. If the angular positions of the cranks were not exactly 120° apart, the phase-differences of the motions will not be exactly one-third of the period. The time-phase of motion must be complementary to the space-phase of angle in the combining mechanism, otherwise the resulting motion will not be a *uniform* rotation. The famous three-phase system of currents (or *Drehstrom*) for producing a rotatory magnetic field, is the electrical analogue of the three-crank mechanism.

We have then two main cases before us—the 2-phase method (sometimes called the "quadrature" method, or, less correctly, the "quarter-phase" method) and the 3-phase method (called by Dobrowolsky "Drehstrom"). The first 2-phase induction motor was described by Baily in 1879, who used commuted battery-currents. The idea of producing rotation by combining two or more alternate currents of different phase, seems to have occurred from the years 1885 to 1888 independently to several persons. Prof. G. Ferraris, Mr. C. S. Bradley, Mr. Nikola Tesla, Mr. Borel, and Mr. von Dolivo Dobrowolsky. Ferraris found that in such a rotating field not only will pivoted magnets rotate, but masses of iron, both solid and laminated, also disks and cylinders of copper, the drag on these being due to the eddy-currents generated in them precisely as in the classical experiments of Arago, in which copper disks were set in rotation in the presence of a rotating magnet. Fig. 458 illustrates a simple form of Ferraris's motor having a copper cylinder pivoted within two sets of coils A A and B B which lie at right angles to one another.

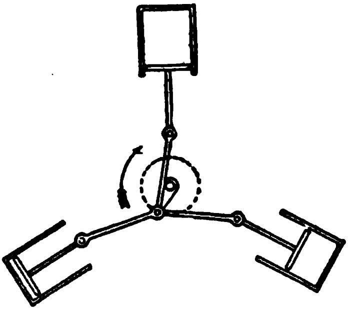

FIG. 457.
THREE-CYLINDER ENGINE.

Ferraris discussed the elementary theory of the apparatus, pointing out that the inductive action would be proportional to the *slip*, that is to say, to the difference between the angular velocity of the magnetic field and that of the rotating cylinder, that the induced current in the rotating metal would also be proportional to this; and that the power of the motor is proportional jointly to the slip and to the velocity of the rotating part.

Consider a laminated iron ring, Fig. 459, wound with two pairs of coils A A′ and B B′, which are inserted in the circuits of a 2-phase generator. At the moment when the current in A A′ is a maximum, that in B B′ will be zero, the currents being in quadrature. The magnetizing effect of A A′ will tend to produce a magnetic field diagonally across the ring in the direction B B′. As the current in A A′ dies down, that in B B′ begins and increases, and therefore shifts the pole forward. When the currents in A A′ and B B′ have become equal, A and B will act together as one coil, while A′ and B will act together as another coil, the resulting poles lying now between B and A′ on the right and between B′ and A on the left. When the B current is at its maximum the poles will lie right under the middle of the A coils. Since there is an actual production here of a travelling polarity in the ring, it follows that any mere mass of iron, a cylinder for example, placed in the rotating field will be set into rotation, though

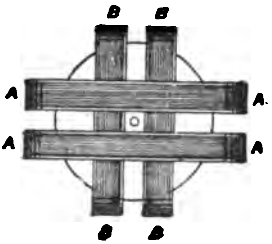

FIG. 458.—SIMPLE ROTATORY-FIELD MOTOR.

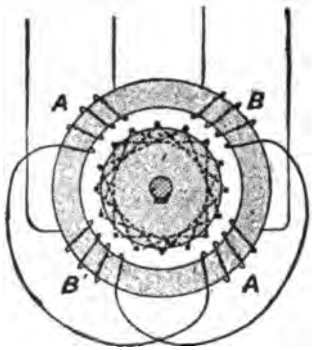

FIG. 459.

not synchronously; and a cylinder of copper would be dragged round by the eddy-currents induced in it. If the cylinder were to revolve at the same rate as the rotating magnetic field, there would be no eddy-currents and no driving force: the rotating part therefore tends to run up toward synchronism but never attains it; for without *slip* (i. e. difference of speed) there would be no induced currents. But if such eddy-currents were permitted to circulate at random in the mass of copper there would be much waste of power in heating, since the only useful currents for driving are those that flow at right angles to the magnetic lines and at right angles to the direction of motion, or, if oblique, their resolved parts in this direction. Hence it is better to make the moving part as an iron core surrounded by appropriate closed coils within which the induced currents are confined. A special form excellent for small motors consists of a cylinder of laminated iron within the periphery of which are embedded a number of stout insulated copper conductors lying parallel to the axis, their ends being united together so that they form closed circuits. A ring of copper at each end—forming with the conductors a sort of squirrel-cage of copper filled with iron—serves to short-circuit the conductors. A short-circuited structure of this kind is shown in Fig. 460.

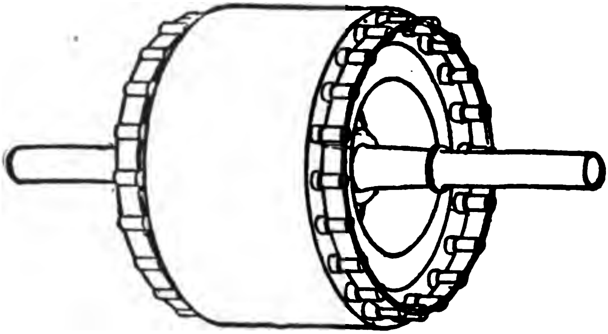

FIG. 460.—ROTATING PART OF BROWN'S MOTOR.

When such rotating combinations of copper and iron are used it becomes a question which part of the machine should be considered as armature, and which as field-magnet. If the ring is regarded as armature, then the copper and iron combination must be looked upon as a field-magnet which is self-magnetized by the eddy-currents in the copper, and which is continually trying to catch up the rotating poles outside it so as to reduce those eddy-currents to a minimum and keep its magnetic polarity constant. If, however, the ring be looked upon as the equivalent of a rotating magnet, then the combination of copper and iron may be considered as an armature in which currents are induced, and which is driven by the reaction of these currents. The former is certainly the more correct view: but to avoid ambiguity it is better to call the revolving mass by the term *rotor*; while the stationary part which receives the primary currents may be called the *stator*.

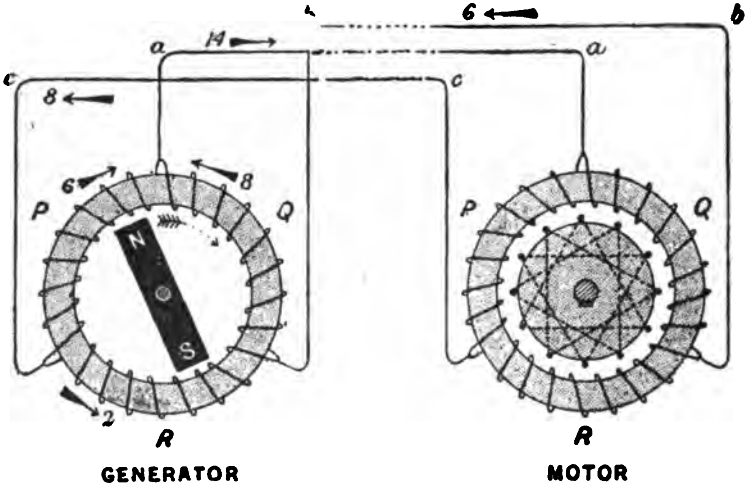

Fig. 461.—Illustration of 3-phase Transmission.

The case of 3-phase currents is illustrated by Fig. 461, where the generator is represented by a magnet revolving within a ring-armature, generating three currents differing 120° in phase from one another. The rings are wound with three coils joined up at their ends and united to three lines. The current in any one line at any instant is equal to the algebraic sum of the currents in the other two; and, with the arrangement shown, the phase of the currents in any one of the lines is intermediate between the phases of the currents in the two coils feeding it. Further, in the motor the current in P differs in phase from the currents in *c* and *a*, being $\frac{1}{12}$ period in advance of the leading current. As the magnet rotates in the generator a pair of travelling poles will, as before, be produced in the ring of the motor. It will be noted that the coils here constitute a closed circuit. There are indeed several ways of connecting up three coils so as to produce the rotatory effect, the following being possible: (1) each of the three coils might be independently joined by two wires to the ends of the three corresponding coils, requiring six lines; (2) three ends of the three coils might be independently joined by three wires to the three corresponding ends of the coils in the motor, their three other ends being united to a common return line, so involving four wires; (3) the three coils *a*, *b* and *c* may be simply joined at a common junction (Fig. 462), from which they branch star-wise each to its own line; (4) the three coils may be joined as *p*, *q* and *r* in Fig. 463, in a closed mesh joined with the three lines at its corners. In this case the phases of the currents in *p*, *q* and *r* are intermediate between those of the three currents in the lines; (5) six coils may be used as in Fig. 464, which shows the way of getting a 6-phase effect out of a 3-phase current by combining the star and mesh arrangements; (6) by merely winding a coil left-handedly instead of right-handedly the phase of its magnetizing force is reversed. For example, a reversed coil inserted

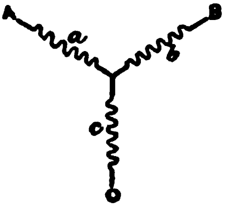

FIG. 462.
STAR COMBINATION.

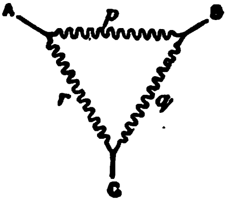

FIG. 463.
MESH COMBINATION.

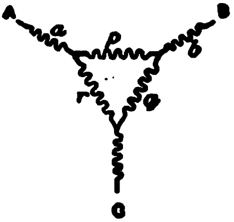

FIG. 464.—STAR AND
MESH COMBINATION.

in a (in Fig. 461) would give an effect differing 180° in phase from a, and therefore intermediate between b and c.

The mode in which the three currents overlap in phase is shown in Fig. 465, the phase-difference being here 120°. Three currents with phase-difference 60° will also serve for rotatory work, and can be converted into three of 120° by merely inverting the connections at the ends of one of the three coils.

Star and mesh combinations may also be applied to 2-phase systems. The two circuits of the Niagara generators are kept separate, four lines being required; but in many cases three lines would suffice, one of them serving as a common return for the two circuits.

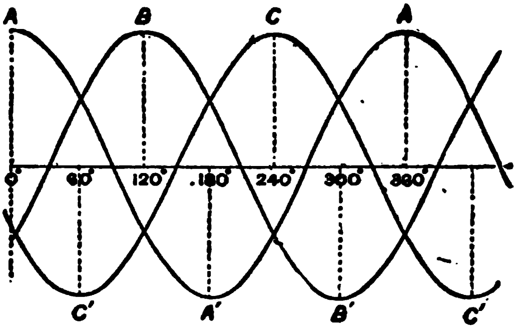

FIG. 465.—THREE-PHASE CURRENT CURVES.

When mesh combinations are used the current in the limb of the mesh as measured by amperemeter differs in value from the current in the line. For a 2-phased system the current in the limb is $\frac{1}{\sqrt{2}}$ of the current in the line. For a 3-phase system the limb-current is $\frac{1}{\sqrt{3}}$ of the line-current. When star combinations are employed, the limb-currents are the same as the line-currents, but the voltages between line and line differ from the voltages between any one line and the common junction. For a 2-phase system with 4-ray star connection, the voltage between two adjacent lines is $\sqrt{2}$ times as great as that from line to centre; while with a 3-phase system it is $\sqrt{3}$ times as great.

Bradley in 1887 described a 2-phase motor (Fig. 466) with mesh connections; the current being brought in by four slip-rings. This, however, was a synchronous motor having a fixed external magnet. In 1889 he described a 3-phase machine, having a similar armature connected at three symmetrical points to three slip-rings.

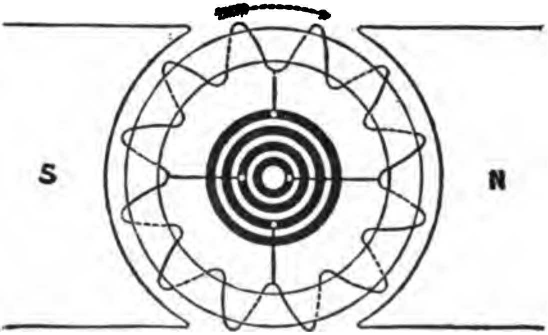

FIG. 466.—BRADLEY'S 2-PHASE MOTOR.

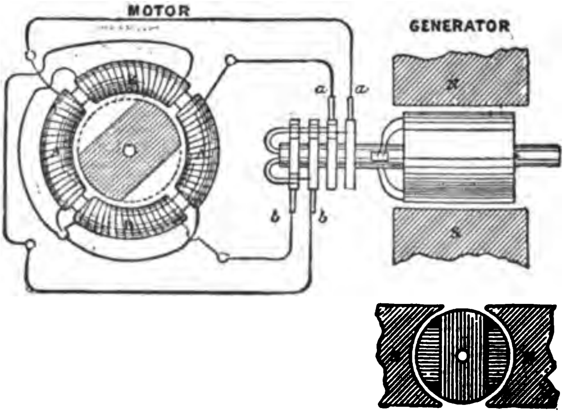

FIG. 467.—TESLA'S 2-PHASE SYSTEM.

Tesla in 1887–88 designed many combinations of which the fundamental notion was the progressive shifting of the field. In Fig. 467 a generator is shown wound with two coils, the free ends of which are connected to insulated contact-rings on the shaft. From four brushes that press on the rings four wires are led away to the motor. This is, in fact, a simple 2-phase generator, inducing two independent currents in quadrature. The motor is shown as a ring having wound upon it four coils, two of which are connected in circuit with one pair of wires, the other two being in the other circuit. They tend to co-operate in pairs to produce magnetic poles on diametrically opposite parts of the ring. Within the ring is pivoted as rotor a disk D of iron, preferably cut away at its sides so as to form an elongated body; and turning so as to convey from side to side of the ring the greatest number of magnetic lines. It was found that this form was not essential to rotation, since a circular disk of iron was also set revolving. In a series of eight diagrammatic figures Tesla explained the successive phases through which the coils of the generator pass during one revolution, and the corresponding and resulting changes of magnetism produced in the ring of the motor.

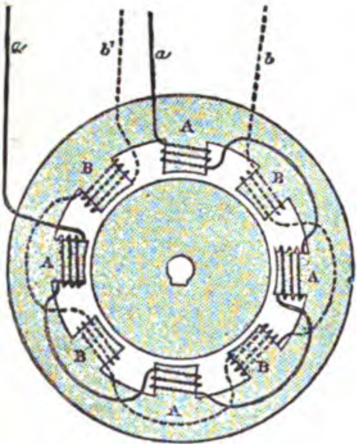

Fig. 468.—Multipolar Design.

By adopting a multipolar design the speed can be reduced though the frequency of alternation remains the same. Fig. 468 shows a design by Tesla for using a tetrapolar magnetic field having four poles in the A circuit (alternately N and S poles), and four intermediate poles in the B circuit. In such a case the progression of the field is not a uniform rotation. The field of a pole at A does not shift round to the next pole at B. What happens is that the magnetism of the A pole dies out, while fresh magnetism grows in the neighboring B pole.

The famous 3-phase transmission of power from Lauffen to Frankfort in the autumn of 1891 did much to bring into notice the advantages of polyphase methods for electric power purposes. Through three copper wires, each 4 millimetres in diameter, and 110 miles long, 100 H.P. was transmitted with an efficiency of 75 per cent., the pressure being raised by transformers to about 8000 volts (see p. 697.) Particulars are given in the author's work on Polyphase Electric Currents.

Modern Polyphase Motors.—In modern motors both stator and rotor are built up of stampings of soft iron pierced with holes or slotted to receive the conductors. Fig. 469 gives about ¼ size the stampings for a 4-pole, 6-H.P., 2-phase motor designed by Brown; the rotor being of the short-circuited squirrel-cage pattern (Fig. 460) with 37 conductors. This motor is intended for 100 volts at a frequency of 40 periods, and runs at 1200 revolutions per minute. Plate XVIII. gives scale drawings of a 3-phase motor of 100 H.P., taking current directly from high pressure mains at 5000 volts, with a frequency of 40 periods per second and a speed of 600 revolutions per minute. The rotor, which is about 30 inches in diameter, has 96 holes through which insulated copper conductors are threaded, and joined up in a wave-winding constituting a 3-branched star, of which the three outer ends are led down through the shaft to three slip-rings to permit of an external starting-resistance being applied. The torque at starting is greater when such resistances are inserted in the secondary circuit (see p. 681). Fig. 470 gives an external view of a 2-phase 120 H.P. motor built upon the same carcase, but with different windings, to work at 2000 volts. In this case the starting resistance is attached inside the rotor, with a simple mechanism passing out through the end of the shaft to short-circuit it when the motor has started. In this way the need of slip-rings is avoided, the rotor having no external connections of any kind.

These rotatory-field motors were brought to a high pitch of perfection by the Oerlikon Co., and by Brown, Boveri & Co.: and more recently the Westinghouse Co. has brought out many fine designs. On the Continent of Europe several large central stations and many factories are now equipped

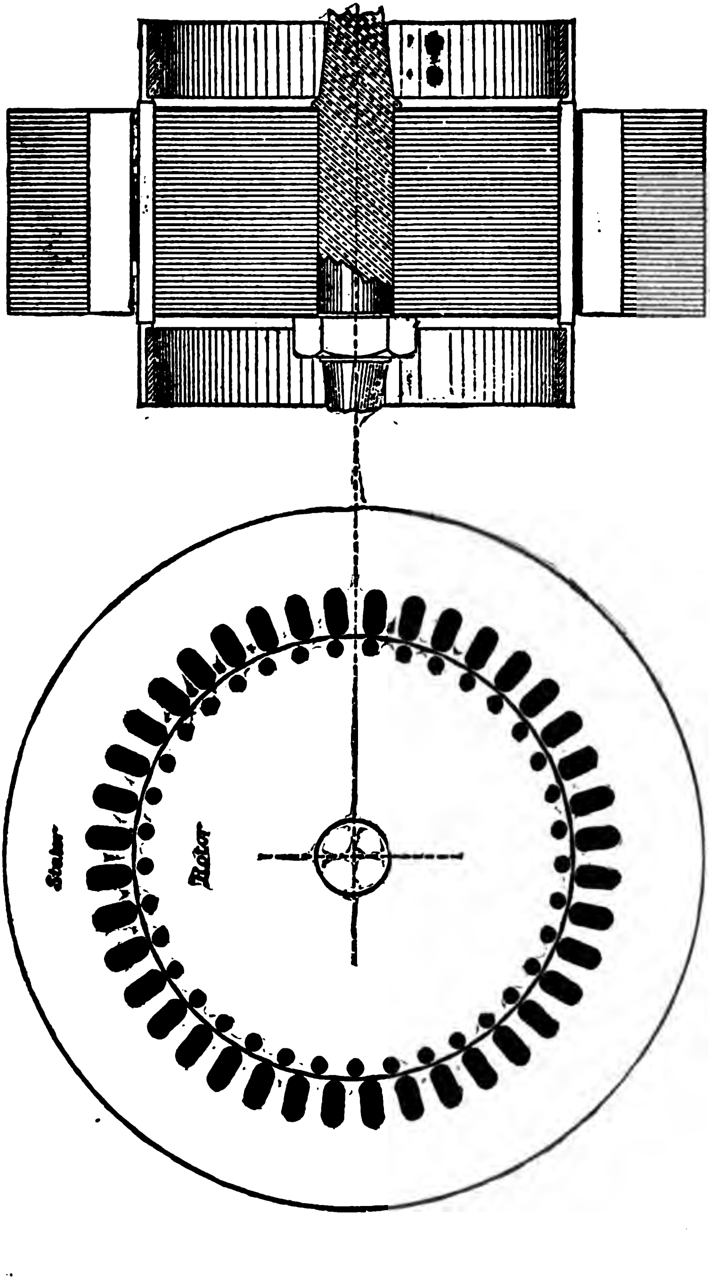

FIG. 469.—STATOR AND ROTOR STAMPINGS (BROWN).

with polyphase systems. The efficiency of the polyphase motors is very high, certainly not inferior to that of continuouscurrent motors of equal power and cost.

ELEMENTARY THEORY OF POLYPHASE MOTORS.

For the sake of simplicity we will take a bipolar machine, the iron of which is of the general shape shown in Fig. 469. Suppose that a rotatory magnetic field is produced by either 2-phase or 3-phase currents in the stator.

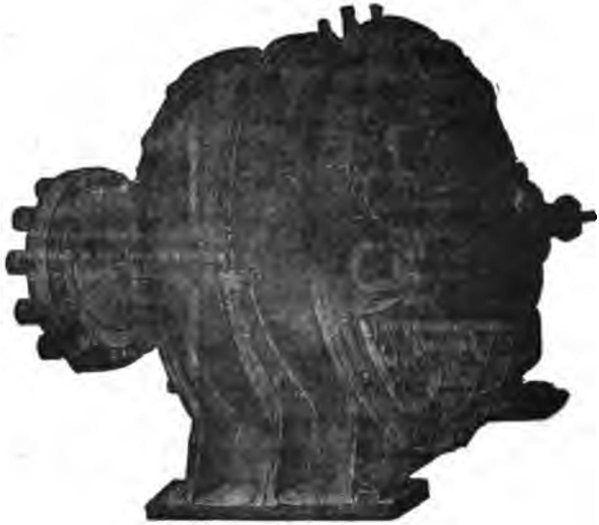

FIG. 470.—TWO-PHASE MOTOR OF 120 HORSE-POWER (BROWN).

The currents in the rotor also produce a magnetic field which, compounded with that of the stator, gives rise to a resultant rotating field. It is to this resultant field that the electromotive-forces in the conductors, and the torque, are due. We will take it as a uniform flux flowing diametrically through the rotor and cutting the conductors of both stator and rotor as it revolves.

Let Ω stand for angular speed of the rotatory magnetic field $= 2\pi n$ in a bipolar machine, where n is the frequency of period. If the machine is multipolar having m pairs of poles then $\Omega = 2\pi n \div m$.

Let ω stand for angular speed of the rotating part, or *rotor* of the machine, $= 2\pi n_2$, where n_2 is the actual number of turns per second.

Let T stand for the torque between the stator and the rotor.

Let W stand for the power (total watts) communicated by the stator to the rotor.

Let w stand for the power (useful watts) actually used in turning the rotor.

$\Omega - \omega$ is the *slip* of the rotor with respect to the field, or is the difference of their angular speeds. If the field has an angular speed $\Omega - \omega$ greater than that of the rotor, it is clear that the inductive action on the circuits of the rotor will be exactly the same as if the rotor were revolved backwards with a speed $\Omega - \omega$ while the field stood still.

$W - w$ is the power wasted in heating the conductors and iron of the rotor, since it is the difference between the total power supplied to the rotor and the power it utilizes.

Now W is proportional to T and to Ω, and therefore, by choosing suitable units may be written $W = T\,\Omega$.

And w is proportional to T and ω, and may be written $w = T\,\omega$.

Hence, dividing the last equation by the preceding,

$$\frac{w}{W} = \frac{\omega}{\Omega}.$$

From this we see that the efficiency of the *rotor* is the same as the ratio of the two speeds. The efficiency of the stator will be considered presently.

Further, the rotatory-field motor is simply a sort of running transformer, of which the stator and rotor windings constitute respectively the primary and secondary. Now, if ω were made $= \Omega$ there would be no induced currents in the rotor conductors, the stator would then simply act as a choking coil; hence, it follows that if the condition of supply of the primary currents is that of constant voltage, the magnetic flux through the machine, rotating with speed Ω, will have an approximately constant value at all loads, just as the flux in the core of an ordinary transformer has. This, of course, is only true when the current in the stator coils is unrestricted; it is not true, for instance, if a resistance is put in series with the stator coils, or when the motor is starting without any resistance in its rotor circuit, as will be seen hereafter. Further, if there is very little magnetic leakage in the gap between stator and rotor (as is indeed the case in well-designed motors), the only electromotive-forces in the rotor conductors will be those produced by the resultant magnetic field, and therefore the maximum currents in them will occur when the conductors are in that part of the field where the flux density is a maximum. And as the flux is constant at all loads (subject to the above conditions), it follows that the torque will be proportional to the currents in the rotor. But these are proportional to the slip $\Omega - \omega$: hence, also, it follows that T will be proportional to $\Omega - \omega$, and may be writen $T = b\,(\Omega - \omega)$, where b is a constant depending on the strength of the field, the radius of the rotor, and the length and resistance of the conductors of the rotor.

We may now write :—

$$\text{Useful watts } w = b \,.\, w\,(\Omega - \omega).$$
$$\text{Total watts } W = b \,.\, \Omega\,(\Omega - \omega).$$
$$\text{Wasted watts } W - w = b \,.\, (\Omega - \omega)^2$$

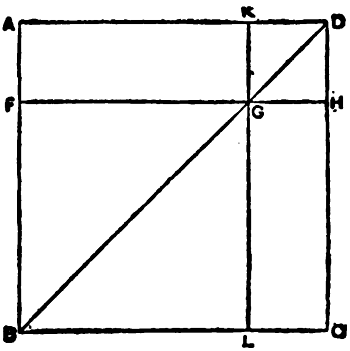

FIG. 471.

Hence we may at once apply the now well-known diagram of motor efficiencies, by drawing (Fig, 471) a square A B C D, having its side A B numerically equal to Ω, and cutting off a piece B F equal to ω. The area A F H D represents the total watts supplied, the area AFGK, or G L C H, the watts utilized, and the square K G H D the watts wasted in heating the conductors of the rotor. The efficiency will approach unity as F moves up towards A; and, as with continuous-current motors, if it were not for the weakening of the field by armature reaction, the output would be a maximum when $\omega = \frac{1}{2}\,\Omega$, the efficiency being then only 50 per cent. We shall see presently that when the motor is running at much below its proper speed, magnetic leakage and other causes play such an important part that the torque is actually less than at a higher speed. Fig. 471 is, however, applicable to cases of normal running, and shows how these rotatory-field motors behave in an exactly similar manner to continuous-current motors.

In good modern rotatory-field motors the slip is only, at the most, about 4 per cent., except for very small sizes of machine, where it may be 10 per cent. at full load.

In the above investigation no account has been taken of the loss due to heating in the conductors of the primary or stator circuit. This, like the ordinary C^2R loss in the exciting circuit of any dynamo, is but a small percentage of the whole energy supplied. Neither has any account been taken of hysteresis losses in the iron of the stator, which also have to be supplied, as it were, by additional excitation, but are small in a well-designed machine. Losses by hysteresis or by eddy-currents in the iron of the rotor will, like the friction of the journals, deduct from the available power, but these are necessarily very small since the reversals of the magnetism in the rotor are proportional not to Ω but to $\Omega - \omega$.

Resultant Magnetic Flux in Motor.—It was pointed out above, from consideration of transformer analogies, that the magnetic flux in the motor is of approximately constant value at all normal loads. We may take it that in the air gap between rotor and stator the flux-density varies approximately as a sine function around the periphery from point to point. Let the density of this flux in the direction in which it is a maximum be called B. This flux-density, like the flux-density in a transformer core, is the result of the magnetizing actions of both the primary and the secondary windings. Kapp has given[1] a discussion of the reaction which may be summarized as follows:—

Take a line B, to represent (Fig. 472) the maximum of the flux-density in the motor; in a bipolar machine it may be considered as revolving clockwise around O as a centre, with an angular speed Ω. This field is due to the joint action of the impressed field excited by the primary currents in the stator, and of the induced field excited by the secondary currents in the rotor. These rotor currents are in phase with the resultant field (if there is no magnetic leakage), and proportional to it, and to the slip. They may be represented by a length c, set off along the side B. This current c tends to produce a cross-magnetization, p.73, proportional to itself. Let the line b at right angels to B represent this cross field. Here $b = k\,c$ where k is a coefficient depending on the reluctance of the magnetic circuit and the number of windings on the rotor. Complete the triangle B b a by drawing the line a. Then a represents in magnitude and phase the magnetic field that must be impressed by the primary currents in the stator, since B is the resultant of a and b. The angle β is the angle by which the current in the rotor lags behind the impressed field.

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[1] Gisbert Kapp, *Electric Transmission of Energy*. 1894, p. 310.

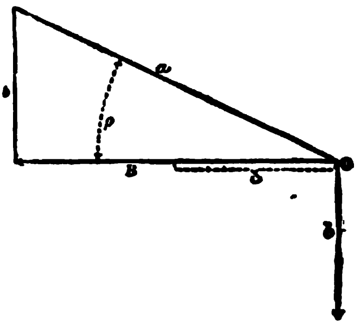

FIG. 472.

Further, since the torque is proportional to both B and c—that is to B and b—the area of the triangle a B b will represent the torque.

Moreover, since c is proportional to the slip,[1] and to B, and to a constant depending inversely on the resistance R in the rotor circuit, we may write

$$c = \frac{\mathsf{B} \times \text{slip}}{\text{R}};$$

$$\text{or slip} = \frac{c\,\text{R}}{\mathsf{B}};$$

---

[1] "Slip" is here used to denote an angular speed, namely $(\Omega - \omega)$. Some writers use it to denote the ratio between the two speeds, that is to say $\frac{\omega}{\Omega}$.

and substituting $b \div k$ for c,

$$\text{slip} = \frac{b}{\mathsf{B}} \times \frac{\text{R}}{k}:$$

but $b \div \mathsf{B}$ is tan β, hence slip is proportional to R tan β. That is to say, if the slip is great the angle of lag β will be great.

Conditions of Operation.—There are three chief stages of operation to be considered; and for the present we will consider the supply voltage constant.

(i.) *Starting.*—Here $\omega = 0$, and slip $= \Omega$. Rotor currents enormous, primary currents also enormous. Therefore, β the angle of phase-difference between primary currents and resultant field very large. Torque would be enormous if there were no magnetic leakage (see p. 681).

(ii.) *Running at Light Load.*—Here ω is very nearly equal to Ω; and as slip is small, rotor currents will be small, and their reaction small. Angle β will be small, and a will not be much larger than B.

(iii.) *Running with Heavy Load.*—Here $\Omega - \omega$, the slip, must be enough to allow of the generation in the rotor of currents enough to produce the necessary torque at the actual speed of rotation.

In addition to the above, if the speed is artificially brought up to synchronism by supplying from without power to overcome friction, &c., there will be no rotor currents and no torque. If the speed is artificially increased beyond this, so that the rotor runs faster than its field, power will be consumed in driving it, and it will act as a generator, pumping back current into the supply network, as we shall see presently (see p. 685; also p. 606).

Starting Torque.—In the above we have considered a motor working under normal conditions, so that the rotor currents are not excessive and the effect of magnetic leakage has been neglected. When, however, the motor is being started, the slip is so great that enormous currents would be generated in the rotor circuit if of low resistance. These currents would call for very large currents in the primary coils to keep up the magnetic flux, just as in a transformer.

The effect would be threefold. In the first place, a considerable fraction of the pressure of supply would be lost upon C^2r losses in the stator coils. Secondly, the ampere-turns of the stator and rotor coils, opposing each other with very great magnetomotive-forces, would force a number of lines along paths which do not thread through both sets of coils (for example, leakage would appear along the air-gap), and these lines would be the cause of electromotive-forces in the stator and rotor coils, in addition to the electromotive-force produced by the common resultant field, and have a choking effect upon the currents in these coils. Thirdly, not only is the true resultant field B diminished by the above causes, but the little that remains is out of phase with the current in the rotor circuit, so that the torque is very much reduced instead of being increased by excessive slip when the rotor circuit is of low resistance. This is very simply exhibited in Mr. Kapp's construction. When the slip is great, the triangle $a\,\mathsf{B}\,b$ will become of the form of Fig. 473; for if slip is proportional to R tan β, and R is small, tan β must be very great, β will be near 90°, the impressed field a is limited by the foregoing considerations, so the torque (represented by the area) will be very small. If we increase R we necessarily decrease tan β, making B greater and the area greater, and so we get a greater starting torque. Thus, introducing a non-inductive resistance into the rotor circuit at starting enables the machine to start with a greater torque.

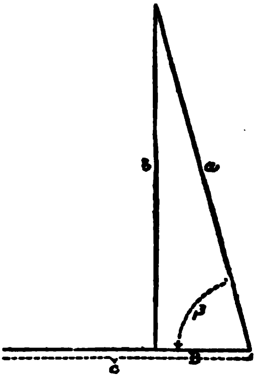

FIG. 473.

Relation between Torque and Slip,—In order to get an equation for the torque in terms of the slip and the resistance of the rotor, we note that from Fig. 472 it follows that

$$b = a \sin \beta,$$

and

$$\mathsf{B} = a \cos \beta.$$

Now, from the equation—slip $= \frac{b}{\mathsf{B}} \times \frac{R}{k}$, we get $\frac{\text{slip}}{R} \times k = \frac{b}{\mathsf{B}}$. Therefore, by merely altering the scale of Fig. 472, we can rename the sides of the triangle as shown in Fig. 474, where s stands for the slip.

From this we see that $\sin\beta = \frac{k\,s}{\sqrt{R^2 + k^2 s^2}}$ and $\cos\beta = \frac{R}{\sqrt{R^2 + k^2 s^2}}$.

Therefore the torque T, which is proportioned to $b \times \mathsf{B}$, is proportional to $a^2 \sin\beta \cos\beta$; and therefore, writing q as a quantity involving a^2 and constants depending on construction, we have

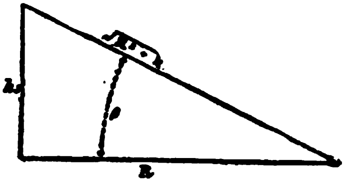

FIG. 474.

$$T = q \cdot \frac{s\,R}{R^2 \times k^2 s^2}.$$

Here we are assuming that a, the impressed field, is constant (see p. 681).

If we wish to see graphically what this equation means, we may then plot out the relation between T and s as a curve, assuming a definite value for R.

Take the line O X (Fig. 475) to represent the speed of rotation of the magnetic field, and cut off from it a part O Q to represent the speed of the motor. Then the remainder Q X represents the slip. This is equivalent to plotting the slip backwards from X. The vertical ordinates then represent the values of the torque as calculated from the equation. For example, when Q X is taken as s; P Q is plotted to represent the corresponding value of T. Thus, beginning at X where the slip is zero, we get a curve X P t_1, which rises steeply, comes to a maximum, and dies away to the value O t, which is the torque at starting. The torque has a certain maximum value for which $\beta = 45°$. It will be noted that the steep end part of the curve is nearly straight, being an asymptote to a straight line, which would represent the relation between torque and slip if the current in the stator were unrestricted and the magnetic field constant. In fact, this line corresponds to the expression $T = b\,(\Omega - \omega)$ on p. 677. Or if in our present equation we consider that values of s are small compared with R, the equation might be written $T = q\,\frac{s}{R}$, giving a straight line law. At the other

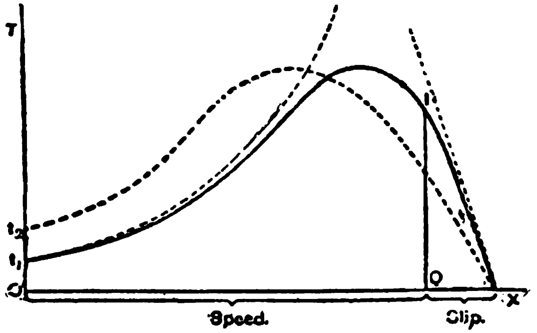

FIG. 475.

end of the curve, where slip is great, the curve is hollow. Here we may approximate by supposing that s is very great compared with R, or that R^2 is small compared with s^2; in which case the equation reduces to $T = q\,\frac{R}{s}$. This is the equation to a hyperbola (also shown in dot). When the motor is at rest $s = \Omega$, or O Q = zero, giving at O t_1 the value $T = q\,\frac{R}{\Omega}$. That is to say, *at starting*, the torque is proportional to the resistance of the rotor. If we then assign a higher value to R, and plot out a new set of ordinates, we obtain a new curve (shown in dotted line) which also starts at X, rises to a maximum of the same height as before, and then falls, but this time to t_2. The effect, then, of introducing more resistance is to raise the torque at starting; but it also has the effect of causing the maximum torque to occur when the slip is greater. The motor gives out practically the same power as before, but runs with a greater difference of speed between its speed at light load and its speed at full load. And the efficiency at full load is diminished. If, with a 5 per cent. slip and a 95 per cent. efficiency, we do not get a sufficient starting torque, we can get it by introducing resistance, and contenting ourselves (at full load) with, say, a 10 per cent. slip, and a 90 per cent. efficiency. And one understands the reason for the modern device of constructing the rotor so that a resistance can be put in at starting, and then short-circuited as soon as the rotor has got up a fair speed.

In the various theories of the rotatory-field motor[1] the subject is attacked from many different points of view, but, through whatever mathematical intricacies it has passed, the expression for the torque is of the general form

$$T = q \frac{sR}{R^2 + k^2 s^2}.$$

The above method of deducing the formula, though incomplete in so far as it does not contain symbols for all the quantities concerned, perhaps has the advantage of keeping clearly in view the main principle, and enabling the student to follow the physical meaning of the expressions throughout. The quantity k, it will be remembered, is a constant, depending upon the reluctance of the magnetic circuit and the number of windings on the rotor. It is, in fact, the self-induction of one complete turn of conductor on the rotor. The quantity q involves a^2 and total number complete turns upon the rotor. In comparing with the formulæ given by other writers, it must be remembered that s is an angular speed, and is equal to $2\pi(n - n_2)$ (see p. 676).

---

[1] By Duncan, Hutin and Leblanc, Sahulka, Picou, Arnold, Ferraris, Reber, Steinmetz, De Bast and others. See the author's work on *Polyphase Electric Currents.*

Steinmetz gives the formula for finding the torque in pounds at 1 foot radius in the form

$$T = \frac{f e^2 g^2 s R}{R^2 + k^2 s^2},$$

to use our own symbols; g being the ratio of the secondary turns to the primary turns, and

$$f = \frac{550}{746 \pi p n},$$

where n is the frequency, and p the number of poles. Steinmetz's theory is very complete in this respect, that he takes into account both leakage and hysteresis, and gives an expression for e, the counter electromotive-force in the stator conductors, in terms of the impressed volts, and an expression involving these quantities. Plotting values for torque at different amounts of slip he gives the curve shown in Fig. 476, which is of the same character as that given in Fig. 475, only

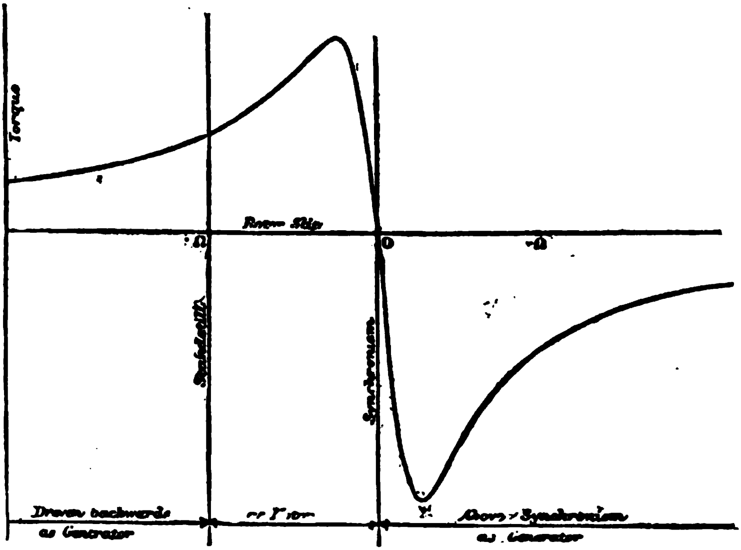

FIG. 476.

extended in both directions. If the speed of the motor is run up by mechanical means beyond synchronism, the torque becomes negative and the machine acts as a generator, giving the lower branch of the curve. If, on the contrary, the motor is turned in the sense opposite to the rotation of the field, the torque decreases as shown on the left of the figure.

The Stanley-Kelly Two-phase Motor.—This motor has the characteristic peculiarity that though a two-phase motor, the two magnetic fields are kept independent and are not combined to form a rotatory field. The stator (Fig. 477) consists of two parts, each of which is multipolar, and which are "staggered" with respect to one another. Each simply produces an alternating field. The revolving part consists of two rotors side by side (Fig. 478), the windings of which are interconnected, so that the wire which lies directly under the poles in one of the stationary armatures, is in series with the

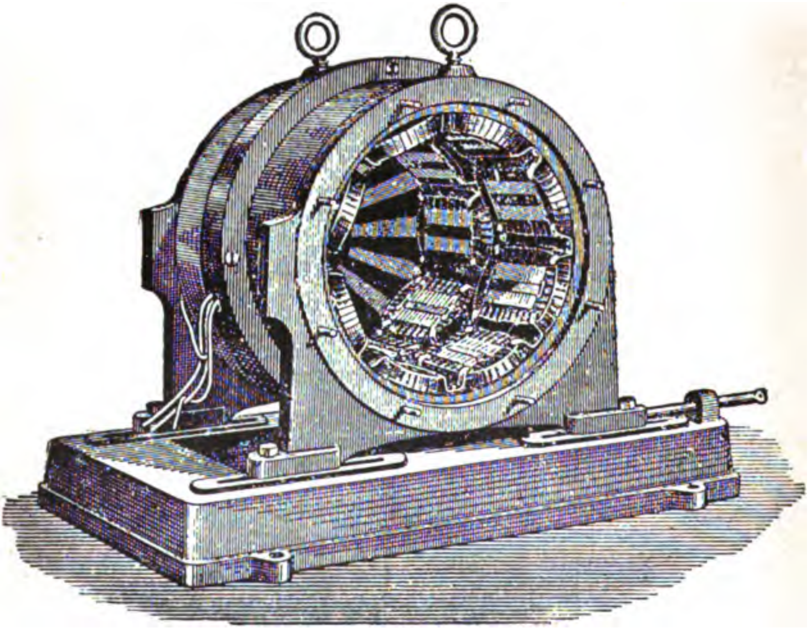

FIG. 477.—STATOR OF STANLEY-KELLY MOTOR.

wire that lies between the poles in the other. So connected each rotor acts alternately as a motor, to receive current and be driven by it, and as a transformer to send current to the other rotor. The windings on the two rotors together are closed, having no external connections or commutator.

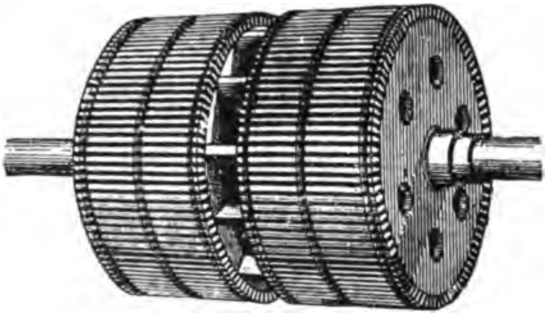

FIG. 478.—ROTORS OF STANLEY-KELLY MOTOR.

MONOPHASE MOTORS.

As soon as polyphase asynchronous motors had reached the stage of practical success, it became evident that monophase asynchronous motors might be constructed on analogous lines. Many years ago De Fonvielle discovered that an iron disk pivoted within a coil supplied with an alternate current was mantained in rotation if once started in either direction. Even before the introduction of polyphase methods the fundamental fact had been discovered by Prof. Elihu Thomson, that if a short-circuited armature is set into rotation between the poles of an alternating electromagnet, it will tend to go on in the direction of its motion and increase its speed. The alternating magnetic flux through a non-moving rotor will induce strong currents in those conductors which enclose it; but there will be no more tendency to turn in one direction than in the other. But Elihu Thomson found that owing to the lag caused by self-induction, the current in the closed circuit reacts, tending to produce a secondary magnetic field which is out of phase with the primary or impressed field.

Hence, if this secondary field is compounded at an angle with the primary field, the resultant action will be equivalent to a rotatory field.

In the course of his observations on the effects of alternate currents,[1] in 1886-7, Elihu Thomson observed that a copper ring placed in an alternating magnetic field tends either to move out of the field or to turn so as to set itself edgeways to the magnetic lines. He took an ordinary continuous-current armature placed in an alternating field, and having short-circuited the brushes, placed them in an oblique position with respect to the direction of the field. The effect was to cause the armature to rotate with a considerable torque. The conductors of the armature acted just as an obliquely placed ring, but with this difference, that the obliquity was continuously preserved by the brushes and commutator, notwithstanding that the armature turned, and thus the rotation was continuous.

A closed squirrel-cage rotor, like Fig. 460. when once started in an alternating (bipolar) field, tends to run up into synchronism; that is to say, if there were no friction it would make exactly half a turn during each reversal of the primary current. But if there is any work done in turning, then it will run slower, the *slip* being proportional (as in the polyphase motors) to the torque. The only trouble then is to start the motion.

Monophase motors may therefore be built on lines precisely similar to the polyphase motors already described. The rotor, for small sizes, may be a simple squirrel cage; for larger sizes it will be a wound structure, with arrangement for inserting a starting resistance. The stator will be wound with appropriate windings to receive the primary current, and with an auxiliary winding to be used at starting, as described below, and then either to be cut out or else thrown into the main circuit.

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[1] Elihu Thomson, "Novel Phenomena of Alternating Currents," *Elec. World*, (N. Y.), May 28, 1887. See also J. A. Fleming, "On Electromagnetic Repulsion," *Proc. Royal Institution*, March 1891; and *Journ. Soc. of Arts*, May 14, 1890.

Splitting the Phase.—The way in which monophase motors are commonly started is to superimpose upon the alternating field an oblique field differing in phase. This is usually done by having additional coils on the stator fed by a current that is out of step with the current in the main coils, and it is necessary to have some device which will cause a difference in the phase of the currents in the two branches. This operation of *splitting the phase* may be performed in many ways. Ferraris produced rotation in his motor by connecting one of the pairs of coils in the circuit of an ordinary alternate current, whilst the other pair were connected as a shunt to the circuit, with an inductive resistance included in order to retard the phase. Borel attained a similar result by using iron cores in one pair of coils.

We have seen (p. 563) that in circuits possessing resistance and self-induction the tangent of the angle of lag of the current behind the electromotive-force is equal to p L/R. If, therefore, we have a comparatively large self-induction in one branch of the circuit, and comparatively large resistance on the other, the phases of the currents will differ by nearly 90°. This difference in the self-induction of the branches may be caused either by the difference in the number of turns of wire in the coils on the stator and the arrangement of the iron around them, or it may be caused by putting in series with one of the branches a coil of wire on an iron core. A non-inductive resistance may be introduced into the other branch.

A difference in phase can also be produced by giving one of the branches capacity by means of a condenser, capacity having the effect of giving the current a lead. The kind of condenser usually employed for this purpose is an electrolytic condenser, consisting of a number of iron plates with a solution of carbonate of soda between them.

Split-phase Motors.—This device of procuring a difference of phase at starting may also be made use of for the permanent running of a motor. Two-phase motors were designed by Tesla in which the two sets of poles were wound with coils having different resistances and inductances. They only need to be supplied, however, from a single source of alternating current.

Theory of Monophase Motors.—Prof. Ferraris [1] has given a simple method of treating this subject in which the alternating magnetic field is regarded as being resolved into two magnetic fields rotating in opposite directions. It is a familiar point in mechanism that any simple harmonic rectilinear motion may be resolved into two equal circular motions in opposite directions. Fig. 479 illustrates one way of doing this, the mechanism being well known to engineers. The amplitude of the original motion is equal to the diameter of each of the circular motions. Ferraris deals, however, with the problems of the alternating magnetic field quite generally, applying the geometrical notion of rotating vectors.

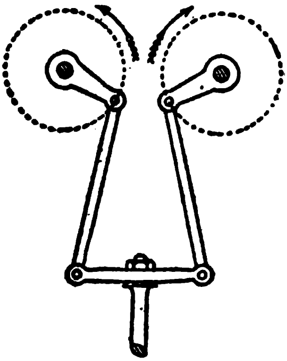

Fig. 479.

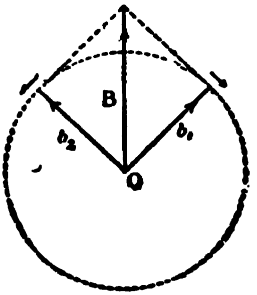

Fig. 480.

If we represent by the vector b_1 which rotates clockwise uniformly about O, the magnitude and direction of a rotating magnetic field, and by b_2 the magnitude and direction of another field of the same strength rotating in the opposite sense with the same frequency n, it will be seen that the direction of the resultant field is always along the line B, and the magnitude of the resultant field will alternate between the values $+ 2\,b$ and $- 2\,b$ following a sine function of the time, so that we may write $B = 2\,b \sin 2\,\pi\,n\,t$.

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[1] Galileo Ferraris, "A Method for the Treatment of Rotating or Alternating Vectors, with an Application to Alternate-current Motors," *Electrician*, 110, 129, 152, 184, 1894.

Conversely, if we have an alternating field following the law $B_0 \sin 2\,\pi\,n\,t$ as in a monophase motor, we may resolve it into two oppositely rotating fields of the same frequency n, and consider the effect of each field separately upon the rotor.

If the rotor turns clockwise with a frequency m, the frequency of rotation of the clockwise field with respect to the rotor will be $n - m$, and the frequency of rotation of the counter-clockwise field with respect to the rotor will be $n + m$.

Each field may be considered as generating currents in the rotor, and the torque due to such currents flowing through conductors in the field may be ascertained by the formulæ employed in the case of rotary-field motors.

Now it was found above (see p. 682) that a field rotating with a speed s relatively to the rotor produced a torque

$$T = q\frac{r\,s}{r^2 + 4\,\pi^2\,L^2\,s^2}.$$

where $L = k$, and the coefficient $2\,\pi$ is added because on p. 682 s was an angular speed, whereas here n and m are revolutions per second.

The torque due to the two oppositely rotating fields will be

$$\text{Torque} = q\,r\left[\frac{n - m}{r^2 + 4\,\pi^2\,L^2\,(n - m)^2} - \frac{n + m}{r^2 + 4\,\pi^2\,L^2\,(n + m)^2}\right],$$

where q is proportional to the number of conductors on the rotor and to the square of the magnetic flux.

It is not necessary to consider the partial torque exerted by the currents due to one rotating field flowing in conductors that are immersed in the *oppositely* rotating field, because the frequency of these currents differs by $2\,m$ from the frequency of that opposite field; and consequently this torque is rapidly reversing in direction.

In order to find the torque due to the field rotating clockwise with the frequency $n - m$, we draw the curve O P Q W

(Fig. 481) (see p. 683 where the curve is reversed) showing the relation between slip and torque obtained by the formula

$$T = q \frac{r s}{r^2 + 4 \pi^2 L^2 s^2}.$$

Let O $Q_{\prime}$ represent the speed of rotation of field of frequency n; then measuring backwards from $Q_{\prime}$ a distance $Q_{\prime}$ $P_{\prime}$ $= m$ (= speed of rotor) we get the abscissa O $P_{\prime} = n - m$, and the ordinate $P_{\prime}$ P represents the torque in question.

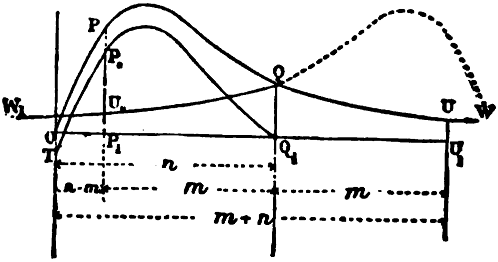

FIG. 481.

To find the torque due to the counter-clockwise rotating field, we measure off forwards from $Q_{\prime}$ the distance $Q_{\prime}$ $U_{\prime} = m$ and get O $U_{\prime} = n + m$, then U $U_{\prime}$ represents the torque due to a slip $n + m$. This being in the opposite sense to the torque P $P_{\prime}$ we can cut off from P $P_{\prime}$ a part P $P_{\prime\prime}$ = U $U_{\prime}$, and obtain $P_{\prime\prime}$ $P_{\prime}$ which represents the actual torque on the rotor. For convenience in subtracting the torques due to counter-clockwise field we may draw Q $W_{\prime}$ symmetrical with Q W, and then subtract the intercepted parts such as $U_{\prime\prime}$ $P_{\prime}$ from the ordinates such as P $P_{\prime}$. Doing this for all the ordinates between O and $Q_{\prime}$ we obtain the new curve T $P_{\prime\prime}$ $Q_{\prime}$, the ordinates of which represent the actual torque for various values of m. When $m = 0$, that is to say, when the rotor is stationary, the two opposite torques balance one another; as m is increased the torque rises to a maximum, and then falls to zero before m is quite as great as n. Any further increase in m produces an opposing torque.

This argument assumes that the impressed flux remains fixed, which is only true so long as the motor is supplied with the same current. The curve cannot therefore be taken as the true characteristic of the monophase motor supplied at constant voltage, but is useful as a simple indication of its general behavior, When load is thrown on to the motor its speed decreases a little, more current flows through the stator, and the impressed field is correspondingly increased, so that the quantity denoted by q increases in reality with the load.

A number of alternate-current motors have been devised which do not come under any one of the preceding classes, and yet are hardly susceptible of classification.

Laminated Series Motors.—For small power an ordinary continuous-current motor with commutator and brushes may be used, provided the field-magnet is built of laminated iron.

Retarded Field Motors.—If one end of a laminated bar of iron is placed in a magnetizing coil supplied with an alternate current, it will undergo an alternating magnetization. But if at a point further along it is surrounded by a stout copper ring or ferrule, the eddy-currents induced in the latter, being out of phase with the primary current, will react locally on the alternating magnetization and retard the phase of the magnetic polarity at all points beyond. Consequently, if two or three such closed rings or bands of copper surround the iron core at different distances along (Fig. 482), the effect will be the same as if the poles travelled along the iron at a finite speed, a north pole being followed by a south pole, and again by a north pole, each travelling toward the tip, and there dying out. On this plan the Ferranti-Wright motor is based. It is used in Ferranti's alternate-current meters. A pivoted iron disk is placed between two curved pole-pieces of laminated iron, each of which is furnished with retarding-rings of copper.

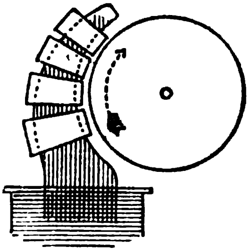

FIG. 482.

CHAPTER XXVI.

TRANSFORMERS.

WHENEVER electric energy is to be transmitted to a distance, considerations of economy dictate that high voltages[1] shall be employed. On the other hand, considerations respecting safety to person as well as those respecting the pressures suitable for lamps, dictate that the voltage at which the energy should be supplied to the consumer should be comparatively low, or from 100 to 200 volts at the most. Hence devices are required which shall receive the currents at high pressure from the feeders or main lines, and shall transform the energy so as to give out larger currents at lower pressures. Such devices are called *transformers*. Notes on the history of transformers were given in the previous edition of this work.

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[1] This is fully explained in Chapter XXVIII. on Transmission of Energy, but may be briefly recapitulated here. It must be remembered that the energy supplied per second is the product of two factors, the current and the pressure at which that current is supplied, or in our notation,

$$\mathcal{E}\,C = \text{electric energy per second (in } \textit{watts}\text{).}$$

The magnitudes of the two factors may vary, but the value of the power supplied depends only on the product of the two; for example, the energy furnished per second by a current of 10 amperes supplied at a pressure of 2000 volts is exactly the same in amount as that furnished per second by a current of 400 amperes supplied at a pressure of 50 volts; in each case the product is 20,000 watts. Now the loss of energy that occurs in transmission through a well-insulated wire depends also on two factors, the current and the resistance of the wire, and in a given wire is proportional to the square of the current. In the above example the current of 400 amperes, if transmitted through the same wire as the 10-ampere current, would, because it is forty times as great, waste sixteen hundred times as much energy in heating the wire. Or, to put it the other way round, for the same loss of energy one may use, to carry the 10-ampere current at 2000 volts, a wire having only $\frac{1}{1600}$th of the sectional area of the wire used for the 400-ampere current at 50 volts. The cost of copper conductors for the distributing lines is therefore very greatly economized by employing high pressures, and using step-down transformers to reduce the pressure to that needed for the lamps.

For transforming continuous currents a revolving apparatus is required consisting, in principle, of a motor (driven by the incoming or primary current) driving a generator, which induces a secondary current at the desired (low) pressure. Such combinations, known as *motor-generators*, are specially considered in the next chapter.

For transforming alternating currents (whether single-phase or polyphase) all that is needed is a stationary apparatus consisting of a suitable core of laminated iron with primary and secondary coils wound upon it—in fact an induction coil. These *alternate-current transformers* form the subject of the present chapter.

GENERAL NOTIONS ABOUT ALTERNATE-CURRENT TRANSFORMERS.

The simplest and earliest form of transformer was the iron ring of Faraday, Fig. 483, upon which he wound two coils, a primary and a secondary. In elementary treatises on electricity it is explained how an electromotive-force is induced in the secondary whenever the primary current is increasing or diminishing, because the magnetic lines made in the iron core by the primary current thread through the secondary coil and act inductively. The same thing occurs in the form shown in fig. 484, where the two coils are wound one outside the other upon a straight core of iron wires.

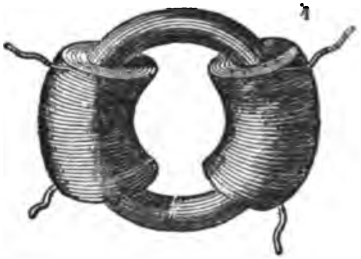

FIG. 483.—FARADAY'S RING, WITH PRIMARY AND SECONDARY COILS.

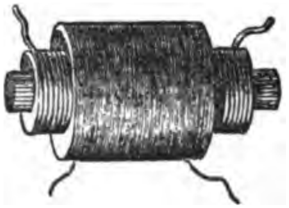

FIG. 484.—SIMPLE INDUCTION COIL, WITH STRAIGHT CORE.

An alternating transformer may be regarded as a species of dynamo, in which neither armature nor field-magnet revolve, but in which the magnetism of the iron circuit is made to vary through rapidly repeated cycles of alternation, by separately exciting it with an alternating current. The primary coil of the transformer corresponds to the field-magnet coil of the dynamo; the secondary of the transformer to the armature coil of the dynamo.

If an alternating current having a frequency of n periods per second be sent into either of the coils there will be set up in the other coil an alternating electromotive-force having the same frequency, because the iron core is undergoing an alternating magnetization also of n cycles per second. The effect on the second circuit is the same as if the magnetized iron core were being plunged into and removed from the second coil n times per second.

Our first step shall then be to calculate the electromotive-force induced in a coil of any given number of turns by an alternating magnetic flux in the core within it. Let S be the number of spirals or turns in the coil, and N the maximum value of the flux in the core. Suppose that the changes of the flux follow a sine law we may then write for the value of the flux at time t after the maximum has occurred,

$$\mathrm{N}_t = \mathsf{N} \cos 2 \pi n t.$$

But the electromotive-force in any one turn is proportional to the rate at which N is changing, or to $d\,\mathrm{N} \,/\, d t$. Further, we must multiply by S, and divide by 10^8 to bring to volts. Performing the differentiation we get

$$\mathrm{E}_t = 2 \pi n \mathrm{S} \mathsf{N} \sin 2 \pi n t \div 10^8.$$

The virtual value of this electromotive-force is obtained by substituting for $\sin 2 \pi n t$ its square-root-of-mean-square value namely $\sqrt{2}$, giving us

$$\mathrm{E} = 4{\cdot}45 n \mathrm{S} \mathsf{N} \div 10^8.$$

This formula is fundamental in transformer calculations.

Now consider a simple magnetic circuit, having wound on it a primary coil of S_1 turns, and a secondary coil of S_2 turns. We may conceive it like Fig. 485; but to avoid complications at first, we will suppose that there is no magnetic leakage, that is to say, all the magnetic lines created by the current in the primary coil thread through the secondary coil. The impressed electromotive-force applied to the terminals of the primary coil sets up a primary current which produces an alternating magnetic flux, and this alternating flux in turn induces electromotive-forces, not only in the secondary coil but also a back-electromotive-force in the primary. These two induced electromotive-forces will be strictly proportional to the respective numbers of turns, and absolutely in phase with one another. We may write them

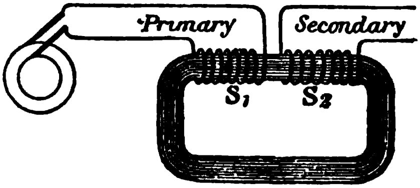

FIG. 485.—ELEMENTARY TRANSFORMER.

$$E_1 = 4{\cdot}45\, n\, S_1\, \mathsf{N} \div 10^8,$$
$$E_2 = 4{\cdot}45\, n\, S_2\, \mathsf{N} \div 10^8;$$

we have, therefore,

$$\frac{E_1}{E_2} = \frac{S_1}{S_2}.$$

This ratio is called the *ratio of transformation*, and is in this chapter denoted by *k*.

Two main cases now arise for consideration: (i.) when the secondary circuit is open; (ii.) when the secondary circuit is closed on a load of lamps or other resistance.

If the secondary circuit is open, though electromotive-force may be induced in it there will be no secondary current, and therefore no reaction of any kind due to this coil. It might as well be absent. The only reaction will be that of the primary coil on itself. As in a motor running light, so in the transformer at no load, the back-electromotive-force will be almost equal to the impressed electromotive-force. The latter must be slightly greater, for there must be enough volts unbalanced to drive the requisite small magnetizing current through the internal resistance of the primary coils; as there are hysteresis and eddy-current losses they also must be provided for by a small additional primary current. But, save for these, the whole action of the primary, when the secondary is open, is that of a *choking coil*, and the induced electromotive-force E_1 will be in almost exactly opposite phase to the primary current.

Now pass to the case where the secondary is closed upon a load of lamps or other resistance. We will suppose this resistance to be for the present a simple non-inductive resistance. There will be a secondary current in phase with the induced electromotive-force E_2, therefore in phase also with E_1, therefore in almost exact opposition of phase to the primary current. When the primary is rising to its maximum, the secondary will also be rising to its maximum, but flowing the opposite way round. While the primary is magnetizing the secondary is demagnetizing; and it is clear that the magnetic flux, on which the counter-electromotive force in the primary depends, cannot be as great as before unless more current flows from the primary source. In fact, more current will of itself flow in the primary because of the demagnetizing effect of the secondary current. The effect of the presence of the current in the second circuit is then to *unchoke* the primary. The primary coil now acts not as a choking coil to dam back the primary current, but as a *working* coil, inducing current in the secondary by flowing sufficiently strong to keep up the alternating magnetic flux in spite of the demagnetizing tendency of the secondary current. If only half the lamps are on, then the primary will act partly as a choking coil and partly as a working coil. If the primary impressed volts are kept constant, the secondary volts at the terminals of the lamp circuit will be nearly constant also; and the apparatus becomes beautifully self-regulating, more current flowing into the primary of itself when more lamps are turned on in the secondary circuit.

The elementary theory of this simple case of a transformer without leakage, working on a non-inductive load of lamps, is quite easy. Adopting the same notation as used for motors and dynamos, write $\mathcal{E}$ for the volts of supply as measured at the primary terminals, and e as the volts at the secondary terminals. Let r_1 be the internal resistance of the primary and r_2 that of the secondary. Call the ratio of transformation $k = S_1 / S_2 = E_1 / E_2$. Since (apart from small hysteresis losses, here neglected) the work done *by* the fluctuating magnetism of the core is equal to the work done *on* it, we may further write $E_1 C_1 = E_2 C_2$; whence it follows that $C_1 = C_2 / k$. The volts lost in the primary are $r_1 C_1$; those in the secondary $r_2 C_2$. Hence we may write

$$\mathcal{E} = E_1 + r_1 C_1,$$
$$e = E_2 - r_2 C_2.$$

Writing the first of these as:

$$E_1 = \mathcal{E} - r_1 C_1 = \mathcal{E} - r_1 C_2 / k,$$

and inserting E_1 / k for E_2 in the second equation, and substituting, we get

$$e = \frac{\mathcal{E}}{k} - \left(\frac{r_1}{k^2} + r_2\right) C_2;$$

which shows that everything goes on in the secondary as though the primary had been removed, and we had substituted for $\mathcal{E}$ a portion of it proportional to the number of windings, and at the same time had added to the internal resistance an amount equal to the internal resistance of the primary reduced in proportion to the square of the number of windings.

Example.—In a Mordey 1½ kilowatt transformer, $S_1 = 300$; $S_2 = 12$; $r_1 =$ 10 ohms; $r_2 = 0{\cdot}014$ ohm; $\mathcal{E}' = 1000$; find e when $C_2 = 36$ amperes. Here $k = 25$, so that on open circuit the secondary volts would be exactly $\frac{1}{25}$ of the primary volts, or 40 volts. But working out by the formula for the output of 36 amperes the terminal volts e drop to 38·92.

CONSTRUCTION OF TRANSFORMERS.

The function of the core is to carry the magnetic lines that are created by the circulation of surrounding currents, and to excite inductive actions in those coils. It is therefore obvious that in the construction of a transformer the core must have a sufficiently great sectional area; further, that its shape ought to be such that all the magnetic lines created by the primary coil shall pass without leakage through the aperture of the secondary coil; and to accomplish this the magnetic circuit ought to be a closed circuit of compact form, and with as few joints as possible. If there is magnetic leakage, so that some of the lines made by the currents in one of the coils do not thread through the other coil, then each coil will tend partially to choke its own currents, and the drop in volts at full load will be greater than that which results (as above) merely from internal resistances.[1] To avoid inductive drop then, we must use such a construction that there is a minimum tendency to magnetic leakage. It is also important to keep the form of the magnetic circuit as compact as possible, so that the necessary magnetic flux may be attained with as few ampere-turns as possible. If by avoiding joints and gaps in the magnetic circuit, by using the most permeable iron, by having the length of path along the circuit as short as may be, and by having a sufficient cross-section of iron, the magnetic reluctance is kept low, then a very small magnetizing current will be needed. This is of great importance in all transformers that are to be used for light all-day loads.

For high-efficiency transformers it is also necessary to avoid those kinds of iron that have much hysteresis (p. 137), and to use sheets so thin (about 0·5 millimetre or $\frac{1}{50}$ inch is the usual limit) that eddy-current losses are kept small.

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[1] Another way of stating this result is as follows :—As will be shown at the end of this chapter, the effect of there being a coefficient of mutual induction between two circuits, is to diminish the self-induction of each of them separately ; or if their convolutions are wound around the same core, in geometrically identical relations, the effect of the mutual induction is to wipe out the separate self-inductions. Any unbalanced self-induction in either circuit will necessarily tend to make that circuit act as a choking-coil; and any magnetic leakage will act as an unbalanced self-induction.

As a further constructional point it is not unimportant to choose such forms as will permit the coils to be wound in a lathe, and to be mounted and dismounted without undue labor.

Return now to Fig. 483 which depicts Faraday's ring-transformer. Its iron core was not laminated; and the placing of the two coils was such that there was a great tendency to magnetic leakage across the ring from top to bottom. Two obvious improvements are (1) to make the core of wire or washers; (2) to wind the primary and secondary coils in sections, sandwiched between one another, as in Fig. 486.

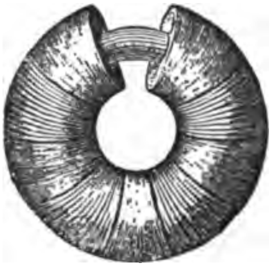


FIG. 486.—RING TRANSFORMER, WITH SANDWICHED COILS.

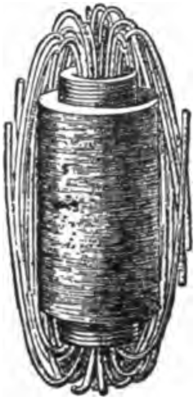


FIG. 487.—VARLEY'S CLOSED-CIRCUIT TRANSFORMER.

Now turn to Fig. 484, p. 695, which depicts the cylindrical type of induction coil, also used by Faraday, further developed by Callan, Masson and Ritchie, and perfected for spark purposes by Ruhmkorff. It has a bad magnetic circuit; for the magnetic lines will have to find their return paths through the surrounding air: it will take a relatively large magnetizing current, and there will be some leakage, through not quite as much as if the two coils had been wound separately on the two ends of the core instead of over one another. Fig. 487 depicts a form due to Varley, which is an obvious improvement, the magnetic circuit being much better closed. The modern Pyke and Salomons transformer is like this, but has the coils sandwiched along the core. The Ferranti transformer, Fig. 499, also resembles this form, but has its core of ribbons of sheet iron. If we imagine the two coils made quite short and set side by side on the core, the elongated form of Fig. 487 might be reduced to the squat shape of Fig. 488, which is a form introduced by Zipernowsky. The primary and secondary coils are first laid upon one another, and the iron core is then wound through and over them by a shuttle, so that the whole of the copper is enclosed within the iron. In the drawing (Fig. 488), the front portion of the iron winding is represented as removed to show the interior. Mr. Kapp has proposed the name of "shell-transformers" for this type of apparatus as distinguished from those with a mere straight or a non-expanded internal core, which he calls "core-transformers." But the two types run into one another. All shell-transformers have a core, and all core-transformers, if they have closed magnetic circuits at all, have some portion of iron returning outside the windings; so it is only a question of detail how far this return portion is spread out as a shell. It is certain that excellent transformers are made in accordance with both extremes of type.

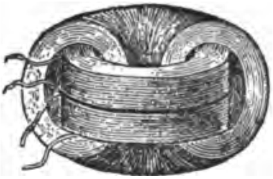
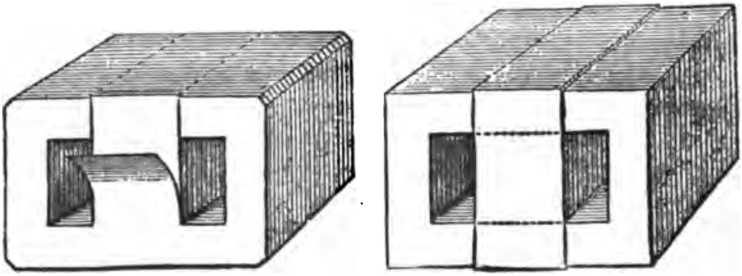


FIG. 48.—8ZIPERNOWSKY'S SHELL-TRANSFORMER.

Types of Modern Transformers.—Modern transformers, almost without exception, have cores built up of thin sheet stampings. The forms shown in Figs. 489 and 490 are typical of a class in which the stampings when assembled constitute a long central core and an external shell, with two long apertures to receive the coils. Different firms build up the stampings differently, and wind the coils in different ways.

To avoid waste of material Mordey introduced the method shown in Fig. 490, where the cross-pieces that form the core are simply the rectangular portions stamped out of the external plates that form the shell. If the external dimensions of the shell-plate are 6 by 4 inches, the core-plates will be 4 by 2 inches, and each of the windows will be 2 by 1 inches. These pieces are interlaced as shown, being built up, however, around the coils (not shown in Fig. 490) which are previously wound upon a light rectangular former A, Fig. 491, made of hard wood steeped in ozokerit.



Figs 489 and 490.—Core-plates of Transformers (Westinghouse and Mordey).

Fig. 492 shows in diagram four different ways of disposing the primary and secondary windings in the space available in the apertures. Apart from an allowance for the small extra amount of primary current for magnetizing, the quantities of copper needed for primary and secondary are equal (for minimum heat-waste and drop); for if the secondary wire has only $\frac{1}{k}$ as many turns as the primary it will have to carry k times as much current, and therefore require a section k times as great. It is usual to make the primary of a round wire well insulated, and the secondary of insulated copper ribbon or rectangular strip. And as the insulation of the fine primary wire takes up a relatively greater space, the total space left for the primary is greater than that for the secondary. Owing to the conditions of imperfect ventilation a high amperage cannot

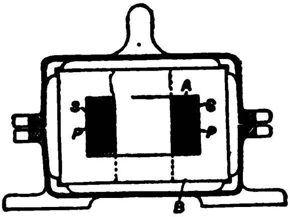


Fig. 491.
Mordey's Transformer
(Transverse Section).

be used; a current-density of 500 amperes per square inch being considered rather high. (Refer to table, p. 371).

In Figs. 493, 494 and 495 are depicted, without showing the jointing of the cores, three types of construction now most in vogue. The first of these is the long shell type just discussed; with its exceedingly compact magnetic circuit and its elongated coils built on a special frame. The second represents a type used by the Oerlikon Co. (compare Fig. 496) having a long core over which the coils, wound in cylindrical shapes on bobbins, can be slipped, the shell-yokes being then added, being furnished with faced joints. This feature of placing the windings cylindrically over one another upon a long core is found excellent for avoiding leakage and inductive drop, and it therefore gives good regulation. As will be noticed, an approximation to cylindrical form is procured by

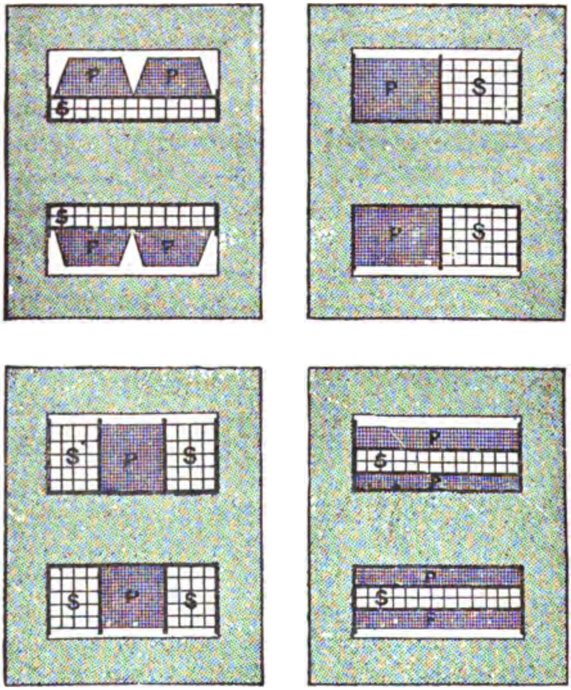


FIG. 492.—VARIOUS MODES OF DISPOSING TRANSFORMER WINDINGS.

use of graduated sizes of core-plates. The fine-wire high-voltage winding is divided into two parts for the purpose of keeping far apart the portions which differ greatly in potential; and the winding is coned at its ends so as to obviate the use of bobbin cheeks; insulation in oil or air being better without them than with them.

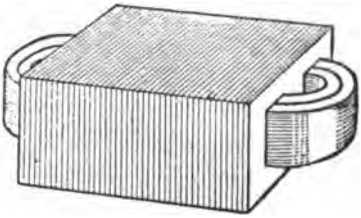


Fig 493.

The transformer now built by Brown, Boveri & Co. has a similar internal core, over which, on a paper cylinder, is slipped the secondary winding of copper strips, and over this again the primary winding in two coned coils: but the yoke part is not in two portions as in Fig. 496, but in one of double section fitting by faced joints.

The form represented in Fig. 495 is that adopted by Messrs Johnson and Phillips, originally from the designs of Mr. Kapp, and may be described as an improved Faraday ring. Dobrowolsky employs a kindred pattern. Plate XIX. gives drawings, the material for which was principally furnished by Messrs. Johnson and Phillips, who have patented several improvements. The cores as shown in that plate are built up of varnished plates of graduated

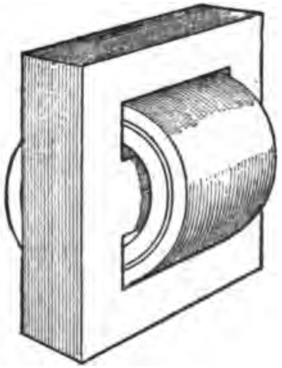


Fig. 494.

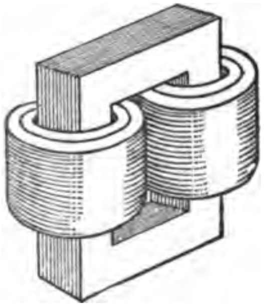


Fig. 495.

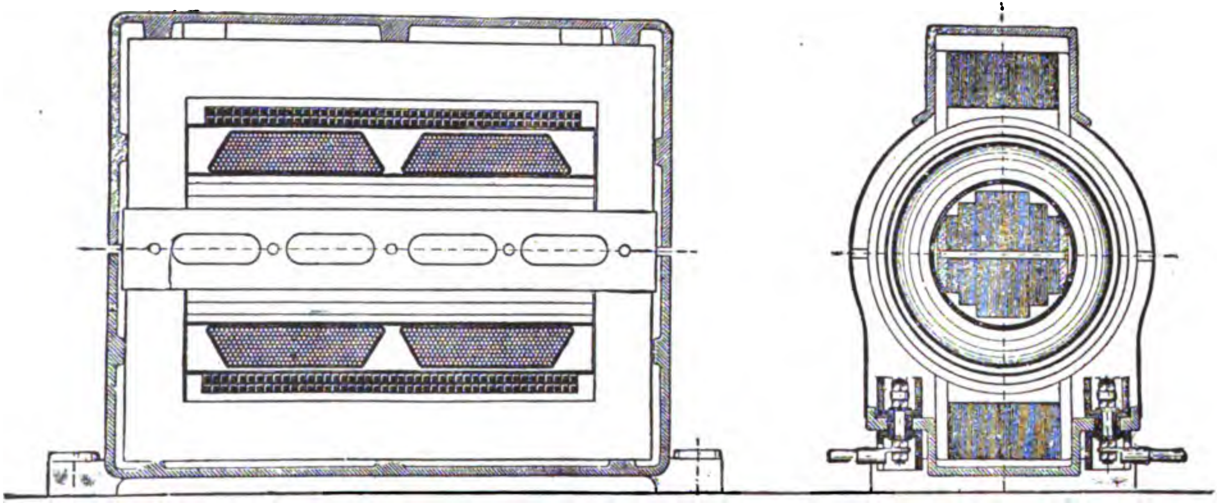


FIG. 496.—OERLIKON CO.'S 20-KILOWATT TRANSFORMER.

sizes, so that the section of each limb is approximately octagonal. The cores are served with tape and coated with shellac varnish. The stampings are in rectangular strips imbricated at the joints, and secured by insulated bolts. Sleeves of insulating material receive the coils, which being cylindrical are slipped over one another on the longer limbs of the core. Afterwards when placed concentrically on the core, sheet ebonite is interposed between them; the fine-wire primary lying outside the secondary. A cast-iron watertight case encloses the whole.

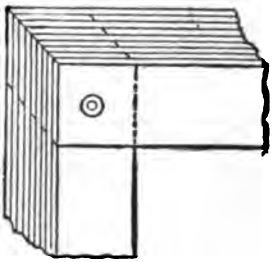


FIG. 497.
IMBRICATED JOINTS.

Fig. 498 illustrates the so-called "Hedgehog" transformer of Swinburne,[1] having as core a bundle of iron wires which, after receiving the copper coils, are spread out at their ends so as to reduce the magnetic reluctance, which is in any case great, the magnetic circuit being an open one. It was supposed to be more efficient, as the weight of iron is so small, reducing the eddy-current and hysteresis losses. But owing to its incomplete magnetic circuit it requires a very large magnetizing current, and therefore at low loads wastes a disproportionate amount of energy in the primary mains. It is now generally agreed that closed-circuit forms are preferable: they have the further advantage of an entire absence of waste from eddy-currents in the copper conductors, however massive.

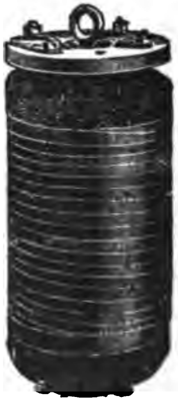


FIG. 498.
SWINBURNE'S
HEDGEHOG
TRANSFORMER.

Ferranti's transformer (Fig. 499) for extra high pressure work, has a core made of a large number of thin strips of iron, which pass vertically up through the middle of the copper coils, and are bent round below and above on each side, and interlapped so as to complete the magnetic circuit. The coils are made of copper strip, very carefully insulated, and compacted together in sections by insulating material. There are three coils thus built up, the innermost being a portion of the primary, outside this the secondary, and outside this again the rest of the primary. Sheets of ebonite are interposed in the spaces between these coils, so as to prevent sparking across from the high-pressure coils. There is also room for air ventilation in the vertical spaces where these sheets of ebonite are wrapped round between the three piles of coils.

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[1] *Journal Inst. Electr. Engineers*, xx. 183, 1891.

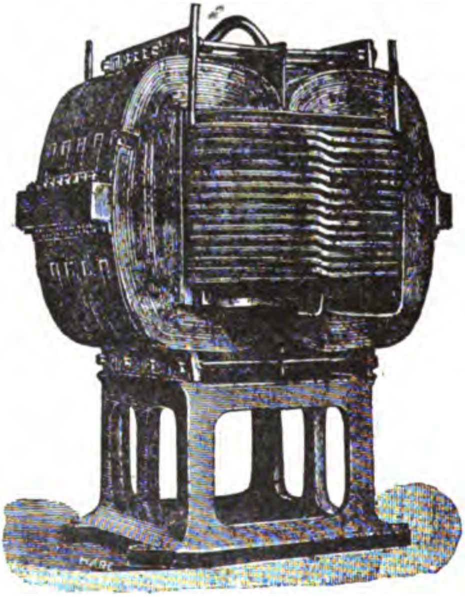

FIG. 499.—FERRANTI'S TRANSFORMER.

Phase-relations in Transformers.—Keeping in mind always as the chief consideration in the operation of a transformer, the alternating magnetic flux in the core, we must next study the relations to it of the other quantities. It may be remarked that in a system of supply at constant voltage, this flux scarcely varies between no load and full load. As in a compounded dynamo, so in a regulated transformer, to keep the volts at the terminals of the lamp-circuit constant needs at full load an increase of but 2 or 3 per cent. in the magnetic flux to compensate for the drop. To simplify matters we will suppose, however, that a drop is allowed to occur, but that the flux always alternates around the same cycle. Also, for simplification, suppose the ratio of transformation to be = 1, so that ampere-turns in each coil may be plotted to same scale as amperes. For any other ratio it will at any time be easy to substitute any given value of the ratio k. Then $E_1 = E_2$, and both are at right angles to the line N O N, Fig. 500, which on the clock diagram represents the time when the flux is at its maximum in either direction. Consider first the case of no load; then the only current will be that in the primary, and if there were neither hysteresis nor eddy-currents in the core it would be an entirely watt-less current, in quadrature with the primary impressed volts, but in phase with flux. Let the value of this *magnetizing current* C_m be represented by the line O C_m. But as hysteresis and eddy-currents put a small load upon the transformer there will necessarily be a small component of current C_p in phase with the volts. This may be represented by the line O C_p. The actual no-load current will be the resultant of O C_m and O C_p, namely O C_o. The *power factor* at no load will be the ratio of the true watts to the apparent watts, or is $C_p \div C_o$. To furnish the small electromotive-force O v requisite to drive the current C_o through internal resistance of the primary, the impressed primary volts must have a magnitude and phase, such that O $\mathcal{E}$ shall be the resultant of O E_1 and O v. But as the no-load current is, say, only 3 per cent. of the full current, and as the primary lost volts at full load will not be more than 2 per cent., O v will not be more than about $\frac{1}{1500}$ of O E_1, and the difference of phase between O $\mathcal{E}$ and O E_1 will be insignificant..

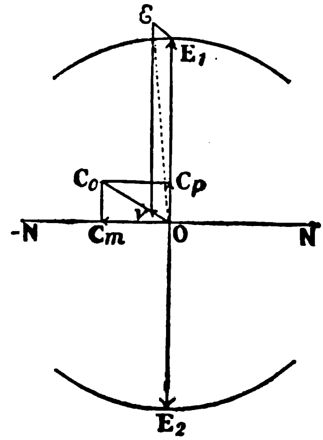

FIG. 500.

At full load the phase relations are somewhat different, and they differ according to whether the load on the secondary circuit is a plain resistance, or as to whether it is inductive, causing a lag of the secondary current behind E_2. If we consider the latter case it will be easy to see what difference the absence of self-induction would make. As before, take for reference the phase of the flux, and work backwards to find the relative phase of the impressed primary volts. The secondary induced electromotive-force E_2 will, as before, be at right angles to N O N.

Now, if there is inductance in the secondary, as well as resistance. there will (see p. 563) be a lag such that $\tan \phi = p L_2 \div R_2$; and the effective volts $R_2 C_2$, that drive the secondary current through the resistance, will be got by the construction in the lower part of Fig. 501. The length O C_2 may be taken as the effective secondary volts; and the actual volts at terminals e might be found by deducting from O C_2 a short length to represent the lost volts $r_2 C_2$. The secondary current also will be represented in phase by O C_2, and by a suitable change of scale O C_2 might also represent it in magnitude. Producing O C_2 backward to an equal length, and compounding this line with O C_0 (the no-load current) we get O C_1 to represent, according to scale chosen, either the primary current or the primary ampere-turns. Along the same line we take the part O v to represent the volts needed to drive this current through the mere resistance of the primary windings. We shall now have to compound O v with the counter electromotive-force O E_1 induced in the primary by the core; and at the same time we must take into account the unbalanced self-induction in the primary (if any) by drawing a line $x\,\mathcal{E}$ $(= p\, L_1\, C_1)$ at right angles to O C_1. This gives as the final resultant, showing required magnitude and phase of the impressed primary volts, the line O $\mathcal{E}$. Consideration of the diagram will show that the smaller the no-load current the more nearly would C_1 and C_2 be in complete opposition of phase; also that self-induction in the primary throws the phase of E_1 behind $\mathcal{E}$, and that self-induction in the secondary

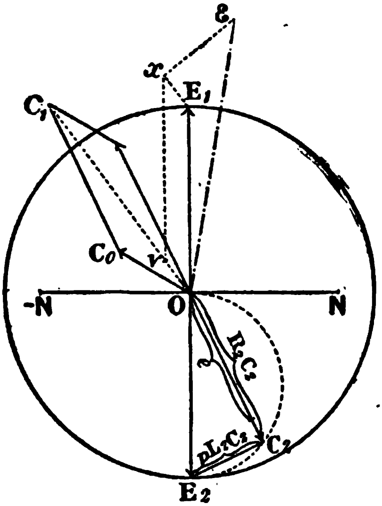

Fig. 501.

throws C_2 behind E_2, hence leakage, which throws self-induction into both circuits, tends to shift the lines O $\mathcal{E}$ and O C_2 nearer to one another.

The actual performance of transformers has been carefully examined by Prof. H. J. Ryan,[1] who has plotted out curves to show the forms and phases of the several varying quantities. The transformer used was a small one of 600 watts capacity, adapted for transforming down from 1000 to 50 volts, the number of windings being 675 in the primary, and 35 in the secondary coil. The volume of laminated iron was about 2050 cubic cm. The mean length of the magnetic circuit was 30·8 cm. and mean cross section 63·3 sq. cm.; the frequency used was 138. Figs. 502, 503 and 504 show the results. It will be noted that although the primary current curve differs widely from a curve of sines (especially at light loads), nevertheless the curve of secondary volts is much more nearly like a sine curve; and it is always in almost exact opposition of phase to the curve of primary volts.

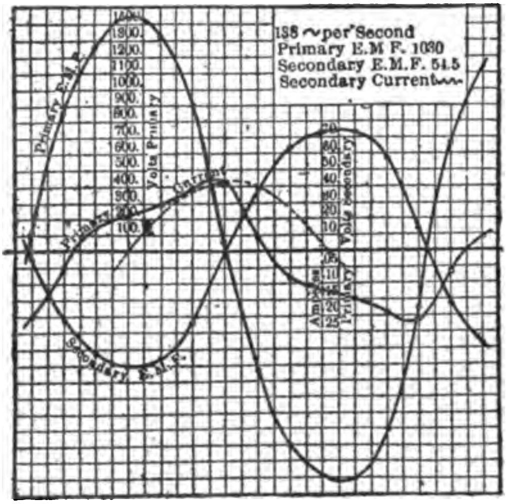

Fig. 502.—Transformer Curves on Open Circuit.

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[1] *Amer. Inst. Electrical Engineers*, 1889 and 1890. See also *Electrical World*, xiv. 419, Dec. 28, 1889, and xvi. 10, July 25, 1890; also *The Electrician*, xxiv. 263, and xxv. 313, 1890; also *La Lumière Électrique*, xxxv. 233, 1890. See also an appendix paper by Messrs. Humphrey and Powell in *Electrical World*, xvi. 11, 1890, and *The Electrician*, xxv. 280, 1890.

In a second paper Ryan shows that the loss of energy by eddy-currents is less when the core is hot than when it is cold. The curious form assumed by the current curve is due solely to the properties of iron. If the impressed primary volts follow a sine law, that of the magnetizing current and of the primary current at low loads will obviously not have the same form unless the permeability were constant. At that stage of things when permeability is increasing with the flux-density (i. e. when B is between 1000 and 6000, see Fig. 92), the current need not increase so fast as to conform to the sine curve; but at the stage when the permeability is decreasing while B is increasing (i. e. when B has passed 8000), the current must increase more rapidly than would conform to the sine curve.[1]

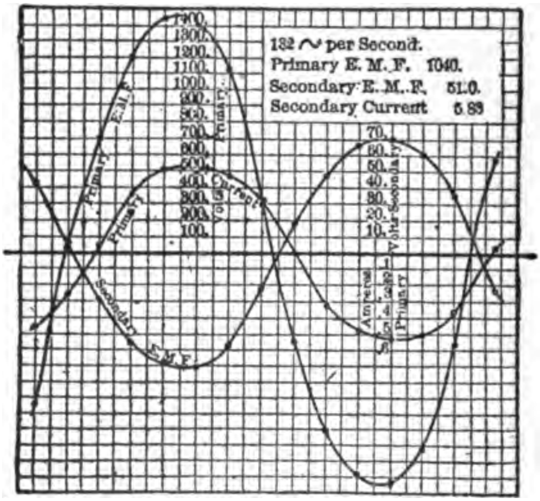

FIG 503.—TRANSFORMER CURVES AT HALF LOAD.

Efficiency of Transformers.—It has been found independently by Steinmetz, by Fleming and by Wedding that the efficiency of a given transformer depends to some extent upon the form of the electromotive-force impressed by the generator, a peaked form giving a higher efficiency, a flat-topped, square-shouldered form giving a lower efficiency than a pure sine curve. The reason depends on the fact that the hysteresis losses increase disproportionately with the higher flux-densities. For, since the value of the volts at any instant depends on the rate of change in the magnetic flux, a square-shouldered volt curve will imply a high-peaked curve of flux-density, and *vice versâ*. Dr. Roessler, in a recent investigation[1] on this subject, found that at no load the primary winding when the volts followed a sine law absorbed 1·5 times as much energy as when a peak wave was used. He pointed out that one objection to the peaked wave was that it put a greater stress upon the insulation than a sine wave of the same virtual value.

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[1] See Ryan and Merritt, Fortenbaugh and Sawyer. Major Hippisley, *Proc. Roy. Soc.*, 1892, lii. 255; Fleming, "Delineation of Alternating Current Curves," *Electrician*, 1895, xxxiv. 507; Rimington, E. C. "Alternate Current when E. M. F. is of a zig-zag wave type." *Phys. Review*, iii. 100 (1895).

Many discussions have arisen over the curves of transformers and over the efficiency under various conditions.[2] Fleming[3] in particular has published most valuable determinations of the efficiencies of a large number of transformers. The reader should also consult the writings of Bedell and Crehore, Kapp, Weekes, and Feldmann. The following table gives the principal results of Fleming's tests. The last named on the list had an efficiency of 97 per cent. at full load; and at one-third load had an efficiency of 94·5 when supplied from a Mordey alternator giving a nearly true sine curve, and of 94·9 when supplied from a Thomson-Houston alternator giving a peaked curve.

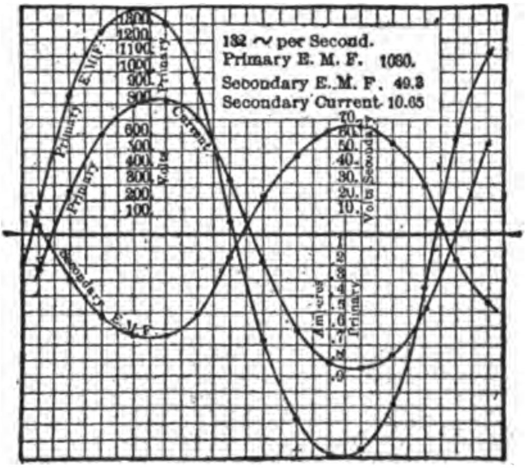

FIG. 504.—TRANSFORMER CURVES AT FULL LOAD.

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[1] *Elk. Zeit.*, August 1, 1895; *Engineer*, August 9, 1895. See also Feldmann, *Electrician*, xxxv. 809; also various writers, *ibid.* xxxiii. 497, 511, 523, 528, 580.

[2] See Mordey, *Inst. Elec. Eng.*, xviii. 609, 1890; Ayrton, *ibid.* 664, 1890.

[3] *Inst. of Elec. Eng.*, 1892, xxi. 594; see Sumpner, *ibid.* 740.

TRANSFORMERS	Full-load Output from Secondary (watts.)	Magnetising Current (amperes).	Primary Volts.	True Power absorbed at no load (watts).	Apparent Power absorbed at no load (watts).	Power Factor.	Iron-loss, in percentage of full load.	Magnetising Current in percentage of full current.	Total Voltage drop at full load.	Voltage drop due to copper.	Voltage drop due to leakage.	Frequency during test.	Efficiency at full load.
Ferranti (1885 type)..	8,750	0·337	2400	540	808	·68	14·6	21·6	..	..	..	83	85·9
" "	7,500	0·25	2435	444	600	·74	5·9	8·1	2·6	1·9	·7	83	90·8
" "	15,000	0·57	2389	1019	1868	·75	6·8	9·0	..	..	..	83	91·1
" (1892 type)..	11,250	0·076	2400	148	182	·81	1·31	1·61	3·4	2·75	·65	83	95·5
" "	15,000	0·112	2400	228	269	·85	1·52	1·79	2·1	1·65	·45	83	96·6
Swinburne (Hedgehog).. ..	3,000	0·74	2400	112	1775	·063	3·73	59·0	3·2	2·23	·97	83	93·5
" "	6,000	1·216	2400	165	2920	·05	2·75	47·5	..	..	..	83	96·1
Westinghouse	6,500	0·05	2400	95	120	·79	1·46	1·85	2·4	1·38	1·02	83	96·9
Mordey (Brush Company) ..	6,000	0·076	2400	140	182	·77	2·33	3·05	1·8	1·75	·05	83	95·4
Thomson-Houston	4,500	0·083	2400	108	199	·54	2·4	4·42	3·3	2·47	·83	83	94·7
Kapp (Johnson and Phillips) .	4,000	0·145	2400	152	348	·61	3·8	8·7	1·9	1·83	·07	83	94·2
Mordey (Brush Company) ..	50,000	0·645	2206	934	1423	·656	1·7	2·4	2·45	2·37	·08	100	97·0

DESIGN OF TRANSFORMERS.

In designing a transformer that shall have a given output when supplied from mains that are operating at a given voltage and frequency, there are several modes of procedure; and in many points experience is the only guide. The following is probably the best way to go to work. First select the type of structure, then from economical considerations decide what will be the permissible loss of power in iron and in copper. If the transformer is for all-day use at low loads the iron loss must at all hazards be kept low. If only for use during short periods a large copper loss may be allowed. If it is for motor running a considerable inductive drop is admissible. Having decided how many watts may be lost in the iron, fix, from previous experience, the approximate dimensions of the ironwork. Choose the size of core stampings, and determine approximately the number likely to be wanted for the output. It will be easy to take a few more or a few less if on completing a first calculation some change seems desirable. Then estimate the approximate weight of iron, and from this and the permissible loss in watts calculate the loss per pound of iron. (This should come out from 0·5 to 1·3 watts.) Then refer to the curve, Fig. 91, which connects this loss with the flux-density B, and find the corresponding value of B. If this comes out lower than 4000 or higher than 8000, it will be well at once to go back and take less iron or more as the case may be. Having found a reasonable value for B, estimate (in sq. centimetres) the nett area of section of the core you have chosen, and multiplying this by B you get the flux N. Then from N and the prescribed voltage and frequency you find S_1 by the formula on p. 697, and from S_1 and the ratio of transformation you find S_2.

At this stage it may be well to calculate the no-load current by finding separately the wattless magnetizing current C_m, and the waste-power current C_p necessitated by hysteresis and eddy-currents. The former may be calculated by magnetic-circuit principles, and the length l of the path of the flux along the magnetic circuit and the value of the permeability μ that corresponds to the particular value of B, by the formula

$$C_m = \frac{B\,l}{\sqrt{2}\cdot 0{\cdot}4\,\pi\,.\,\mu\,.\,S_1} = 0{\cdot}565\ B\,l \div \mu\,S_1.$$

The waste-power current C_p is calculated from the power permitted to be wasted in the core, by dividing down by the primary volts. Finally the no-load current C_0 is calculated (see Fig. 500) by the formula

$$C_o = \sqrt{C_m^2 + C_p^2}.$$

Returning to the design, calculate from the drawing (with due allowance for layers of insulation) the mean length of one turn of primary winding, of primary, and of secondary. Then from the available space left for the windings (allowing about $\frac{3}{5}$ of this for the primary winding because of insulation requirements, and $\frac{2}{5}$ for the secondary winding) and the numbers S_1 and S_2 calculate the sections, resistances and weights of copper. Then work out the watts lost in copper at full load and no load, and the current density. If the copper losses come too great you have not left winding space enough, and must take a larger iron core. It depends on the type of structure as to what you can do with a larger core. If it is such that the apertures for the windings (as in Fig. 492) are no larger than before, it will, by having a greater section of iron, have the advantage that N being greater, S_1 and S_2 may both be smaller, and therefore larger sizes of copper wires can be got into the same apertures. If the new core is longer than the old one, but no thicker, you can use the same numbers of turns as first calculated, but thicker wires.

In all cases it is well to work out on paper the effect of two or three different selections, and to choose that which comes nearest to the prescribed conditions. Some capital examples of working out are given by Evershed.[1]

Another method of procedure is to assume an iron core of given dimensions, and fixing frequency and voltages, to work out the windings to give a definite flux-density (say $\mathsf{B} = 5000$) in the iron; and take the sections of the two windings as large as is structurally possible. This leaves the currents undetermined, and leaves the rating of the full-load output to be determined either by the limit of permissible temperature-rise (to be found by experiment, or by calculation from losses and surface) or by the voltage drop, or approximately by the current density permissible, or by the limit of efficiency. Some makers rate their transformers above the output at which the rise of temperature will be within safe limits. The final degree to which after some hours' full working the temperature rises depends on the total losses in iron and copper, on the available surface for radiating this heat, and on the facilities for cooling, such for example as the circulation of oil in the outer case. A usual figure of allowance of cooling surface is 40 sq. centimetres pea watt of loss. At this allowance the temperature rise will be about 50° C. above the surrounding atmosphere if there is no oil cooling, or about 40 degrees with oil in the case. And, within the limits of 15 to 65 sq. centimetres per watt, the temperature rise will vary roughly inversely with the available surface. E. Thomson has suggested the use of perforated secondary conductors to allow of greater cooling surface. The newest Westinghouse transformers have the projecting ends of the sandwiched coils bent away from one another for better ventilation. A forced circulation of oil has been suggested.

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[1] *The Electrician*, xxvi. p. 477 et seq.

If a transformer designed to work at a certain voltage at a given frequency is used for the same voltage at a lower frequency the efficiency will be less : for, from the fundamental formula on p. 696, it is clear that the cycles of magnetization of the iron core must go to a higher maxima of flux density, causing disproportionate losses. If a transformer designed for a 2000-volt circuit at 100 periods is used on a system at 50 periods it ought to be rated at lower voltage, say as a 1000-volt transformer, or else rewound. On the other hand, raising the frequency lowers the flux-density (for the same voltage) and therefore raises the efficiency. If the flux-density is unaltered, the loss per cycle will also be unchanged, and the loss per second will be proportional to the number of cycles per second. Other things being equal it may be taken that for a given copper loss (and therefore for given current) the output is proportional to the voltage, and therefore for a proportional iron loss, is proportional to the frequency. Hence for a given total loss the output of a given transformer is proportional to the frequency. In other words, high frequency means a saving of weight and cost, smaller transformers being used than with low-frequency of supply.

CONSTANT-CURRENT ALTERNATING TRANSFORMERS.

Transformers arranged so that the two self-inductions of the two coils are high compared with the mutual induction between them have been designed by Elihu Thomson and by Stanley for the purpose of yielding alternating currents of a constant number of virtual amperes. Forms with much magnetic leakage answer this purpose. Swinburne[1] has pointed out that a hedgehog transformer will answer in this way if the primary and secondary coils are wound on opposite ends instead of being wound close together. An ordinary transformer can be adapted to such service if a choking-coil is introduced into the primary circuit. The use of constant-current apparatus is for feeding arc and glow lamps in series.

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[1] *Proc. Roy. Soc.*, February, 1887.

AUTO-TRANSFORMERS.

The auto-transformer (or "one coil" transformer) merely consists of a coil of wire wound on an iron core, and connected across the mains. To some point in it, at a greater or less distance from one end, according to the voltage required, a branch wire is attached and current is drawn off between this branch and one end. In Fig. 505 the ends *p p* are attached to the primary mains, while *s s* act as the secondary terminals, giving out a lower voltage, and acting as a pressure-*reducer*. It will be seen that a greater current can be drawn off in this way than is actually supplied by the mains, as the portion of coil that is common to the circuit acts as the secondary of a transformer. Less copper is required than if there were two separate coils. If the connections were made the other way, so that the lesser number of coils were connected to the mains, the voltage at the outer terminals would be raised; the arrangement then serving as an *augmentator* of pressure.

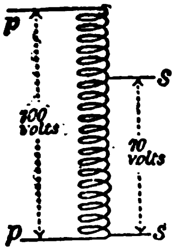

FIG. 505.
AUTO-TRANSFORMER.

For distribution by the 3-wire system the secondaries of transformers are often wound to 200 volts, with a middle terminal half-way along the coil for the third wire of the network. For working three arc lamps in series at 33 volts each, from 100-volt mains, an auto-transformer is used having intermediate terminals, so that each lamp is a shunt to one-third of the coil.

POLYPHASE TRANSFORMERS.

For the special forms of transformers used for 2-phase and 3-phase currents; and for transforming 2-phase to 3-phase currents, or *vice versâ*, the reader is referred to the author's treatise on *Polyphase Électric Currents.*

THEORY OF ALTERNATE-CURRENT TRANSFORMERS.

There are two ways of treating the theory of transformers. In the first, which lends itself the more easily to simple treatment, and has already been used on p. 699, the fundamental consideration is the alternating magnetic flux in the core, which induces electromotive-forces in the two windings, and is itself due to the resultant of the two sets of ampere-turns in the coils. This method has been elaborated by Hopkinson.[1] In the second the calculations are effected by introducing the notion of coefficients of mutual and self-induction into the differential equations for the two circuits. The latter method, due to Maxwell,[2] consists in finding the electromotive-force induced in the second circuit by the variations of current impressed on the first circuit.

First let us consider the coefficients of mutual and self-induction. In order to calculate the mutual action of the two circuits we want to know the amount of cutting of magnetic lines by the *secondary* coils that takes place when unit current is made to flow, or is stopped in the *primary* coils. Let M be used as a symbol for this quantity. It will be proportional to the number of turns in the secondary coil, because each turn encircles the iron core and cuts the magnetic lines ; it will also be proportional to the number of turns in the primary coil, because, *cæteris paribus*, the magnetism evoked in the iron core is proportional to the ampere turns that excite it ; it will also be proportional at every stage to the permeability of the iron core. We may, in fact, calculate M by the magnetic principles laid down in Chapter VI. Suppose the iron core to form a closed circuit of length l, section A, permeability μ ; and that S_1 and S_2 are the respective numbers of turns in primary and secondary. Then, if the primary current is unity (in absolute C.G.S. units), the magnetomotive-force due to it will be $4 \pi S_1$, and the reluctance will be $l / A \mu$. Dividing the former by the latter, we shall have an expression for the number of lines in the core ; this multiplied by S_2 gives the amount of cutting of lines by the secondary circuit ; or in symbols

$$M = 4 \pi S_1 S_2 A \mu / l.$$

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[1] *Proc. Roy. Soc.*, February, 1887.

[2] *Philosophical Transactions*, clv. pt. i. p. 459, 1865. In this paper Maxwell shows that the effect of the second circuit is to add to the apparent resistance and diminish the apparent self-induction of the first circuit. The student will find the equations more fully treated by Mascart and Joubert, *Électricité et Magnétisme*. i. 593 and ii. 834 ; also by Hopkinson, *Journal Soc. Teleg. Engineers*, xiii. 511, 1884 ; Ferraris, *Mem. Acad. Sci.* (Turin), xxxvii. 1885 ; and by Vaschy, *Annales Télegraphiques*, 1885–6, or *Théorie des Machines Magneto et Dynamo-Électriques*, p. 81. A summary of Maxwell's work is given in Fleming's book.

The name given to this quantity is the *coefficient of mutual induction.* If the current in the primary have the value C_1 (absolute C.G.S. units), then the amount of cutting by the secondary on turning this current on or off will be $M\,C_1$. And if the rate of increase or decrease of the primary current at any instant is known, this multiplied by M will give the electromotive-force impressed at that instant on the secondary circuit.

Considerations precisely analogous to those above will show that there will be a *coefficient of self-induction*, which we will call L_1, which represents the amount of cutting, by the primary coil, of the magnetic lines created in the coil when the primary coil carries unit current; and, as before, the value of this coefficient will be

$$L_1 = 4\,\pi\,S_1^2\,A\,\mu\,/\,l.$$

As S_1 is itself usually large, L_1 will be enormous. Further, there will be a coefficient of self-induction L_2 in the secondary circuit, such that

$$L_2 = 4\,\pi\,S_2^2\,A\,\mu\,/\,l.$$

In a well-built transformer it is clear that

$$M = \sqrt{L_1\,L_2}.$$

If, however, all the magnetic lines due to one circuit are not enclosed by the other, M will have a less value than is indicated by the above relation. (See a recent paper by Dr. Bedell read at the Chicago Congress, 1893.)

The ratio between the two electromotive-forces and the two sets of windings,

$$\frac{S_1}{S_2} = k,$$

we will call the *coefficient of transformation.*

If it is assumed that there are equal weights of copper used in the primary and secondary coils, then the following relations will hold good :—

	Primary.	Secondary.	Ratio.
Windings	S_1	S_2	k
Resistance	r_1	r_2	k^2
Self-induction	L_1	L_2	k^2
Electromotive-force	E_1	E_2	k
Current	C_1	C_2	k^1
Heat-waste	$C_1^2\,r_1$	$C_2^2\,r^2$	1

Also
$$M = \frac{L_1}{k} = L\,k_2.$$

Maxwell's Theory.—At any given instant the impressed electromotive-force in the primary circuit must be sufficient not only to drive the current C_1 through the resistance R_1 of that circuit, but must also be adequate to counterbalance the reactions arising from mutual and self-induction. These at that instant will have the respective values $M\,\frac{d\,C_2}{d\,t}$ and $L\,\frac{d\,C_1}{d\,t}$.

Accordingly we write as the differential equation of the first

$$E_1 - M\,\frac{d\,C_2}{d\,t} - L_1\,\frac{d\,C_1}{d\,t} - R_1 C_1 = 0; \tag{1}$$

circuit—where E_1 is the impressed electromotive-force of the generator which is supposed to fulfil the condition $E_1 = D \sin 2\,\pi\,n\,t$ (see p. 549). If the supposition is admitted that a constant (alternating) potential can be maintained at the terminals of the primary coil (by proper compounding of the alternator, or otherwise), then the letters E, L_1 and R_1, may be taken to apply to that part of the primary circuit only which lies between the terminals of the primary coil. From this differental equation we have to deduce a value for $M\frac{d\,C_2}{d\,t}$. For brevity we will write p for $2\,\pi\,n$; and $-p^2\,C$ for $\frac{d^2\,C}{d\,t^2}$, because C is also assumed to be a sine-function. Then differentiating equation (1) we get—

$$\frac{d\,E_1}{d\,t} + M p^2\,C_2 + L_1\,p^2\,C_1 - R_1\,\frac{d\,C_1}{d\,t} = 0. \tag{2}$$

Now multiply this by R_1 to get equation (3), and multiply equation (1) by $L_1\,p^2$ to get equation (4) ; and add (3) and (4) to get (5).

$$R_1\,\frac{d\,E_1}{d\,t} + M\,p^2\,R_1\,C_2 + L_1\,p^2\,R_1\,C_1 - R_1^2\,\frac{d\,C_1}{d\,t} = 0. \tag{3}$$

$$L_1\,p^2\,E_1 - L_1\,p^2\,M\,\frac{d\,C_2}{d\,t} - L_1^2\,p^2\,\frac{d\,C_1}{d\,t} - L^1\,p^2\,R_1\,C_1 = 0. \tag{4}$$

$$\left(R_1^2 + L_1^2 p^2\right)\frac{d\,C_1}{d\,t} = R_1\frac{d\,E_1}{d\,t} + L_1\,p^2\,E_1 + M p^2\left(R_1 C_2 - L_1\frac{d\,C_2}{d\,t}\right). \tag{5}$$

Now multiply every term by $\frac{M}{R_1^2+L_1^2p^2}$, and write the following abbreviations :—

$$\frac{Mp}{\sqrt{R_1^2+L_1^2p^2}}=\frac{1}{k}$$

$$R_1/k^2=\rho,$$

$$L_1/k^2=\lambda,$$

Then

$$-\frac{1}{kM}\left(\frac{R_1}{p}\cdot\frac{dE_1}{dt}+L_1E_1\right)=E_2=\frac{1}{k}E_1\sin(pt-\phi),$$

where ϕ relates to the phase of the electromotive-force ; and we may write equation (5) as—

$$M\frac{dC_1}{dt}=\rho C_2-\lambda\frac{dC_2}{dt}-E_2. \tag{6}$$

Now the differential for the second circuit is—

$$M\frac{dC_1}{dt}+L_2\frac{dC_2}{dt}+R_2C_2=0; \tag{7}$$

there being in this circuit no other electromotive-forces than those due to mutual and self-induction. Inserting in (7) the value obtained in (6), we get as the final equation—

$$(R_2+\rho)C_2+(L_2-\lambda)\frac{dC_2}{dt}-E_2=0. \tag{8}$$

Examination of the quantity k shows us that if R_1 be small enough or p large enough, it becomes equal to $\frac{L_1^2}{M}$; or is the same thing as the ratio of the windings for which we have used the same symbol. Then returning to interpret equation (8) we see that it shows us that the whole effect is equivalent to that which would happen if, the primary circuit being absent, there were introduced into the secondary circuit an electromotive-force equal to E_1 divided by k, and at the same time the resistance were increased by a quantity equal to R_1/k^2, and the self-induction were diminished by a quantity equal to L_1/k^2. If there are equal weights of copper in the two windings $L_2=L_1/k^2$, and $R_2=R_1/k^2$; and the effect when the transformer is fully at work is to make ρ equal to the internal resistance of the secondary, and λ equal to L_2, so that the internal resistance is virtually doubled and the self-induction wiped out.

Professor Perry has contributed several important papers[1] on the theory of transformers, in which he has treated leakage and multiple secondaries mathematically.

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[1] *Phil. Mag.*, August, 1891; and *Proc. Roy. Soc.* li. p. 455, May, 1892.

CHAPTER XXVII.

MOTOR-GENERATORS.

MOTOR-GENERATORS are revolving transformers for affecting transformations which cannot be effected by stationary apparatus. They are of two sorts: (1) for transforming a continuous current at any voltage into a continuous current at any other voltage; (2) for transforming continuous currents into alternating currents (single-phase or polyphase) or *vice versâ*. In every case the apparatus consists essentially of a combination of a motor with a generator.

CONTINUOUS-CURRENT TRANSFORMERS.

Gramme, in 1874, constructed a machine with a ring-armature wound with two circuits—one of coarse wire, the other with fine wire, having eight times as many turns. Two separate commutators were connected with the two windings. This machine could be used for transforming either from high to low potential or *vice versâ*. The same end can be less conveniently attained by uniting on one shaft the armatures of two dynamos, one to be used as a motor driving, the other as a generator; and these may have separate field-magnets or a common field-magnet. There is very little sparking with such machines, as the reactions in the two sets of coils tend to correct each other. The field-magnet is usually excited as a shunt to the low-potential armature coil. Swinburne has discussed many possible combinations, including one for transforming from a constant-current to a constant-potential condition of distribution. The chief use hitherto for continuous-current transformers has been for transmission of current at high voltage, so as to economize copper in the feeding mains. In England, continuous-current transformers have been introduced with success by various firms. Messrs. Laurence, Paris and Scott[1] employ a 2-pole machine with cast-iron frame and an armature wound with double circuits. In the Chelsea central station a number of motor-dynamos are used. They have been described in detail by Major-General Webber,[1] and include several types, some being by Laurence and Scott, others of Elwell-Parker construction. In the city of Oxford continuous currents generated at 1000 volts are transmitted to motor dynamos at several points of the city where they feed the network at 100 volts.

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[1] See *Electrician*, xix. 517, October 1887; and *Electrical Review*, xxii. 4, 1888.

The following are particulars of an Elwell-Parker bipolar continuous-current transformer, with drum wound armature but having a commutator at each end.

——	Primary.	Secondary.
Volts	1000	110
Amperes	40	360
Resistance of armature winding (ohms)	0·427	0·0052
Conductors around armature ..	648	72
Segments in commutator	162	36

Speed 500 revolutions per minute.
Field-magnets: shunt-wound with 3080 turns; resistance 8·5 ohms.
Armature core: diameter of disks 16$\frac{5}{16}$ in.; nett cross section of iron 326 sq. in.
Efficiency of double transformation: at full load 83 per cent.; at half load 75 per cent.

Fig. 506 shows a small continuous-current transformer constructed by the Crocker-Wheeler Co. for the author, for testing purposes. It transforms a current of 10 amperes at 100 volts to one of 1 ampere at 1000 volts. Mr. T. Parker winds motor-dynamos with Eickemeyer coils, the high-pressure windings being completed and connected up first. Then the whole surface is insulated afresh, and the low-pressure windings are laid on in outer layers.

A second use for continuous-current transformers is the production of large currents at very low voltage, as for electrotyping and for meter testing.[2]

A third service for which motor-dynamos are employed is to compensate the drop in voltage on long mains by inserting into the main at a distant point a series motor driving an armature placed as a shunt across the mains. Lahmeyer[3] calls this device a "far-leading" dynamo (Fernleitungs-dynamo). American electricians term it a "booster." Sayers has described such machines fitted with his compensating winding (p. 395). (See *Electrician*, xxxi. 677).

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[1] *Journal Inst. Electrical Engineers*, xx. 63 to 69, 1891, giving drawings and data of three machines.

[2] See *The Engineer*, Aug. 11, 1893.

[3] *Centralblatt für Elektrotechnik*, xi. 402, 1889.

A fourth application is for charging accumulators at a higher voltage than that of the generator, so that the lamps may be run either direct or from the cells.

A fifth use is for 3-wire and 5-wire systems of distribution, a number of armatures or windings on the same shaft being connected across the various pairs of mains. If at any pair of mains the potential drops, this armature will begin to feed this pair, being driven by the other armatures as motors. Such a device is called an "equalizing" dynamo (Ausgleichungs-dynamo.

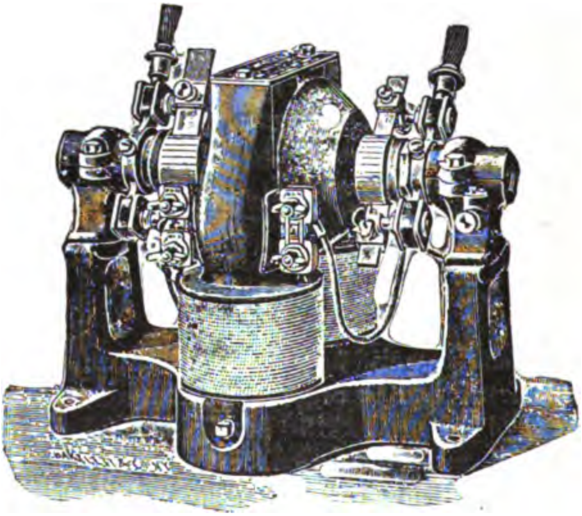

FIG. 506.—CONTINUOUS-CURRENT TRANSFORMER (Crocker-Wheeler Co.).

The following are particulars of transformers or "equalizers," as they may be properly called, recently constructed by Messrs. Mather and Platt for the 5-wire supply in Manchester. The machines have drum-armatures with the bar winding described on p. 306, with shunt-wound magnets of "Edison-Hopkinson" type.

Resistance of magnets	25 ohms.
Resistance of each armature winding ..	.0126 ohm.

With an output on one side of 126 amperes at 103·4 volts, the output on the generator side was 112 amperes at 100·4 volts. Hence the efficiency of double conversion, including all frictional and mechanical as well as electrical losses, is 83·5 per cent.; or looked at from the point of view of the purpose for which the machines are specially intended, if there is a difference of 3·0 volts between the two sides of a 3-wire system, they will transfer 112 amperes from the higher to the lower side. The journals of these machines run on ball bearings.

A somewhat different system of continuous-current transformation has been suggested by Cabanellas,[1] and patented by Edison,[2] in which neither armature nor field-magnet revolves, but in which, by means of a revolving commutator, the magnetic polarity of a double-wound armature is continually caused to rotate. In a further modification of this idea, due to Jehl and Rupp, a mass of iron, which completes the magnetic circuit, rotates within the double-wound ring.[3]

Spark troubles, however, afflict all merely commutating machines.

For further notices of the methods of continuous-current transformation, the reader is referred to articles by Elihu Thomson, in *Electrical World*, x. 108, 1887; by R. P. Sellon, in *Electrician*, xx. 633, 1888; and by Rechniewski, in *La Lumière Électrique*, xxv. 416, 1887; and see *Electrician*, xxxi. 677.

THEORY OF CONTINUOUS-CURRENT TRANSFORMERS.

Let $\mathcal{E}$ be the potentials at terminals of the primary or motor part, and e that at terminals of the secondary or generator part. Let the C_1, r_1, and Z_1 stand respectively for the armature current, armature resistance, and number of armature conductors of the primary part; and C_2, r_2, and Z_2 for the corresponding quantities of the secondary part. Then the two induced electromotive-forces will be—

$$E_1 = n Z_1 \mathsf{N}, \text{ and } E_2 = n Z_2 \mathsf{N}; \text{ and}$$
$$E_1 = \mathcal{E} - r_1 C_1, \text{ and } E_2 = e + r_2 C_2.$$

Now write k for $Z_1 \div Z_2$ (the *coefficient of transformation*), and we have—

$$k e = \mathcal{E} - r_1 C_1 - k r_2 C_2.$$

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[1] See *La Nature*, p. 43, 1882.

[2] Specification of Patent, 3949 of 1882; and *Electrician*, xix. 479, 1887.

[3] See *Electrician*, xix. 514, 1887; xx. 7, 1887; and Specification of Patent, 2130 of 1887.

But the electric work done on and by the armature is equal, assuming loss by eddy-currents and hysteresis to be negligible, or $E_1 C_1 = E_2 C_2$; whence $C_2 = k C_1$, so that the last equation becomes—

$$e = \frac{\mathcal{E}}{k} - \left(r_2 + \frac{r_1}{k^2}\right) C_2.$$

This shows that everything goes on in the secondary circuit as though the potentials were reduced from that of the primary mains in proportion to the respective numbers of windings on the armature ; and as though there were added to the internal resistance of the secondary circuit a resistance equal to that of the primary winding divided by the square of the coefficient of transformation. The ratio of transformation is independent of the speed and of the magnetism, though these two quantities depend inversely on one another, If the dynamo (or secondary) part is compound wound the speed may be very nearly constant at all loads ; but there is little advantage in this, as the speed always adjusts itself to what is wanted. If the distant generator supplying the system is properly over-compounded it will keep the voltage at the lamps constant, though the transformer is interposed. The objections to the use as transformers of running machines are almost entirely met by the considerations that these machines run sparklessly (owing to the balancing of the self-inductions of the two windings), and with very little friction at the bearings, because the driving and driven parts are both contained in the one rotating part. The brushes once set need not be moved at any load.

CONTINUOUS-ALTERNATING TRANSFORMERS.

To change an alternating current to a continuous one, or *vice versâ*, there is required a combination of an alternator and a continuous-current machine, serving one as generator, the other as motor. This may consist of two separate machines coupled together, as shown in Fig. 508, which represents an alternator combined with an internal-pole continuous-current dynamo, both of Siemens' pattern, to transform from 2000 volts alternating to 150 volts continuous, for charging accumulators, &c. The town of Cassel is supplied with continuous currents transmitted as alternate currents at high voltage and transformed down by a Kapp alternator (as motor) driving two dynamos. At Buda-Pesth the transmission is 2-phase, with coupled plant at sub-stations to give out continuous currents.

But it is not necessary for this purpose to couple two separate machines. A single winding revolving in a bipolar field, Fig. 507, joined up not only to two slip-rings, but also to a commutator, will work either as motor or generator for either alternating or continuous currents, and therefore can give out either kind when driven by the other.[1] In practice, a more complex armature with a many-part commutator is used. For example, an ordinary Gramme ring is used with the addition of two slip-rings which are conducted to two points 180° apart. Such a machine has been in use at the Technical College, Finsbury, since 1885, when the rings were added by Dr. Walmsley. It will serve as a transformer either way, or, if driven by power, will furnish either kind of current, or both at once. In 1887, the Helios Co., and in 1889, Mr. Bradley and Mr. Tesla patented similar devices. For producing 3-phase currents from continuous currents, three slip-rings must be connected on at three symmetrical points. For 2-phase currents four slip-rings are connected at points 90° apart. In a recent apparatus of Hutin and Leblanc[2] there is

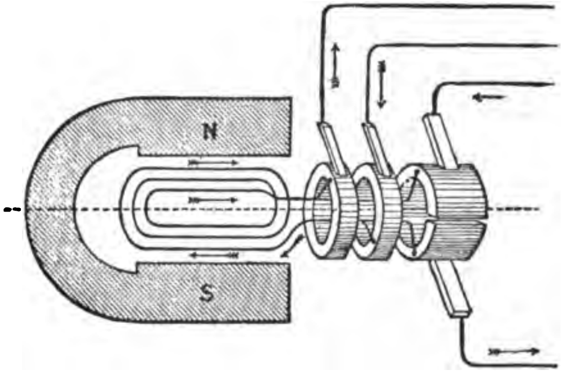

FIG. 507.—SIMPLE CONTINUOUS-ALTERNATING TRANSFORMER.

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[1] M. Hospitalier proposes to call machines of this class *polymorphic* dynamos. See *Soc. Française de Physique*, 1894, p. 204.

[2] See an illustrated article in *L'Électricien* of April 21, 1894.

employed a row of eighteen slip-rings connected at as many symmetrical points, and giving rise to eighteen alternate currents, each differing in phase by 20° from its next neighbor.

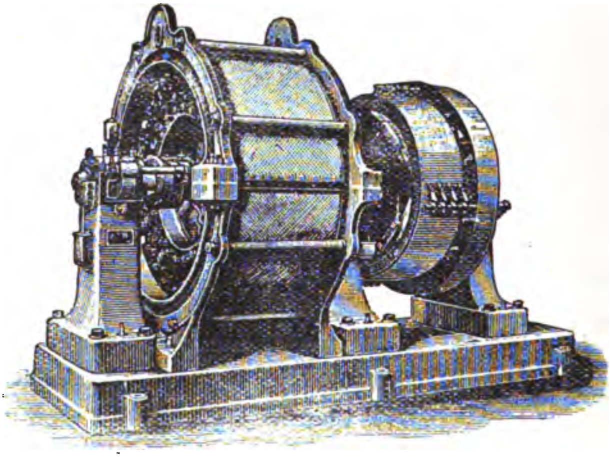

FIG. 508.—CONTINUOUS-ALTERNATING TRANSFORMER.

A simple revolving combined commutator like that of Fig. 509, would, without any field-magnet, suffice to convert continuous into alternating currents, or to rectify alternate currents into continuous, were it not for the practical difficulties arising about sparking. The use of the field-magnet is to balance the electromotive-forces in the different parts of the windings, as well as to maintain the proper rotation.

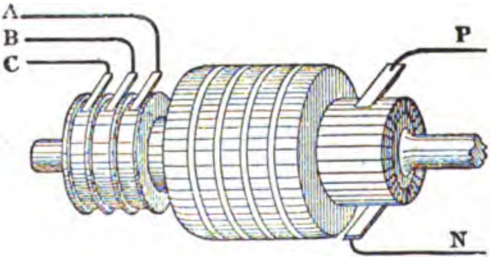

FIG. 509.—TRANSFORMER ARMATURE FOR 3-PHASE AND CONTINUOUS CURRENT.

Pollak, of Frankfort, and Ferranti have both successfully used rectifying commutators, the former for charging accumulators, the latter for arc lighting.

At the Frankfort Exhibition of 1891 many revolving transformers were shown. The firms of Lahmeyer and Schuckert, in particular, displayed many very interesting forms of polyphase apparatus, in which this feature was prominent.

Messrs. Schuckert and Co. showed a six-pole ring-wound machine, capable of transforming from a continuous current or single-phase, 2-phase, or 3-phase currents to currents of any or all of the other three kinds. It consists of an ordinary ring armature with a 144-part commutator, whose windings in front of the different pairs of poles are cross-connected in parallel (Mordey's well-known method). As there are 144 sections in the winding, and six poles, the number of sections that lie between any pole and the next pole of the same sign will be 48. From Nos. 1, 17 and 33, that is to say, at points equally spaced out at distances of one-third of the extent of the winding between any pole and the next pole of the same sign, are attached three wires which are brought down to three slip-rings from which brushes supply 3-phase currents. To four points also equally spaced along the same section of the winding (namely, Nos. 1 13, 25 and 37), are attached four wires, which going to four other slip-rings, supply both single and 2-phase currents.

An 8-pole revolving transformer on a similar principle, but having a wave-wound drum armature, was shown at Frankfort by the Allgemeine Company. It could receive continuous current at about 100 volts, and transform this into 3-phase currents at about 70 volts. This transformer is now in the laboratory of the Technical College, Finsbury.

The most important motor-dynamos yet made are those constructed at Schenectady for the Niagara works.[1]

They are 20-pole multipolar drum machines, having the ordinary commutator, but also having four slip-rings added, at the back of the armature. They receive the 2-phase current already transformed down to 115 volts and deliver 3000 amperes at 150 volts for the purpose of aluminium reduction.

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[1] See *Cassier's Magazine*, 1895, p. 334.

CHAPTER XXVIII.

ELECTRIC TRANSMISSION OF ENERGY.

IN all problems relating to the electric transmission of power, whether over short or long distances, it is vital to remember that the two factors to be considered are the *current* and the *pressure* (or voltage) at which it is transmitted. In the ordinary distribution of electric energy from central stations in cities, whether with direct or alternating currents, it is usual to observe the condition of *constant pressure*, the current being varied in proportion to the demand. But for series lighting, it is possible to observe the other condition of maintaining a *constant current*, the pressure being varied in proportion to the number of lamps in the circuit. It is well to bear this distinction in mind in the problem of transmission to a distance, although in fact power may be electrically supplied without conforming to either of these prescribed conditions of supply. We have seen, p. 492, how it came to be recognized that the secret of success in long-distance transmission lay in the use of high voltages, as this permitted the use of small currents, and therefore of thin conducting wires. We may with advantage recapitulate the problem of economy of transmission.

It is required first to determine the relation between the pressure at which the current is supplied to the motor, and the heat-waste in the circuit.

Let ΣR stand for the sum of all the resistances in the circuit; then, by Joule's law, the heat-waste is (in watts) $C^2 \Sigma R$. And since $C = \frac{\mathcal{E} - E}{\Sigma R}$, we may write:

$$\text{heat-waste} = \frac{(\mathcal{E} - E)^2}{\Sigma R}.$$

Now suppose that without changing the resistance of the circuit we can increase $\mathcal{E}$ to $\mathcal{E}'$, and also increase E to E', while keeping $\mathcal{E}' - E'$ the same as $\mathcal{E} - E$, so that the current will be the same: it is clear that the heat loss will be precisely the same as before, while more energy is transmitted. The efficiency is greater, for

$$\frac{\text{power of motor}}{\text{power of generator}} = \frac{C E'}{C \mathcal{E}'} = \frac{E'}{\mathcal{E}'},$$

and this ratio is more nearly equal to unity than $\frac{E}{\mathcal{E}}$, because both $\mathcal{E}$ and E have received an increment arithmetically equal. As an example, suppose $\mathcal{E}$ to be 100 volts and E 90 volts, and the sum of the resistances to be 1 ohm. Then C will be 10 amperes. The power supplied will be 1000 watts; that utilized will be 900 watts; the heat-waste is 100 watts; and the electrical efficiency 90 per cent. Now suppose the voltages increased so that $\mathcal{E}'$ is 1000 volts, and E' 990 volts. The current will still be 10 amperes. The power supplied will be 10,000 watts, of which 9900 will be utilized and 100 wasted in heat. We have 10 times as much power transmitted, with the same heat-waste as before, and the efficiency has risen to 99 per cent. Clearly, then, it is an economy to work at high voltage.

High voltage can be attained in several ways: by winding armatures with many turns of fine wire, by using higher speeds and by putting several machines in series. In the case of alternate currents there is the additional resource of using step-up transformers (see p. 738 and p. 741).

The advantage derived in the case of the electric transmission of energy from the employment of very high electromotive-forces in the two machines is also deduceble from the diagram.

Let Fig. 328 given on p. 499, be taken as representing the case where $\mathcal{E}$ is 100 volts and E 80 volts. Now suppose the resistances of the circuit to remain the same while $\mathcal{E}$ is increased to 200 volts and E to 180 volts. $\mathcal{E} - E$ is still

20 volts, and the current will be the same as before. Fig. 510 represents this state of things. The square K G H D which represents the heat-waste is the same size as before; but the energy spent per second is twice as great, and the useful work done is more than twice as great as previously.

We may look at the matter from a different point of view. Power being made up of the two factors E and C, if it is required to transmit a certain prescribed number of watts we will by preference make E high and C low, for it is the flow of the current through the resistances of the circuit that causes the loss, while the only disadvantage of a high electromotive-force is the difficulty in preserving the insulation. The electromotive-force will therefore be made as high as it can be made consistently with safety. If we double the pressure, thereby reducing the current to one-half, we reduce the loss to one-quarter, as the loss is proportional to the square of the current.

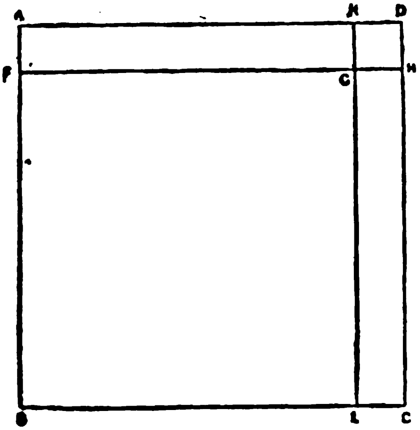

FIG. 510.

In an experiment, M. Fontaine,[1] by using several Gramme machines coupled in series at each end of a line, the resistance of which was 100 ohms, succeeded in transmitting 50 horse-power with a mechanical efficiency of 52 per cent. This experiment realized the suggestion made in 1879 by Elihu Thomson for the economic use of several machines in series. Seven machines were used, of similar construction, of the "over" type, each weighing 1200 kilogrammes, and of about 16 kilowatts capacity. Four were united in series at the generating end, and driven at 1298 revolutions per minute by a steam engine indicating 113 H.P. Brake tests at the generating end showed the actual H.P. to be 95·88. The other three machines were used as motors, their power being measured by a brake. They gave out 49·98 H.P. at 1120 revolutions per minute. The current was 9·34 amperes. The result is that there was a nett efficiency of 52 per cent. The resistance of the machines was about 11½ ohms each. The voltage at the generating end of the line was 5996 volts; that at the receiving end was 5062 volts.

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[1] *L'Electricien*, x. 707, 1886.

Efficiency of Transmission.—It can readily be shown that with two series dynamos, the electrical efficiency of transmission, when there is no leakage, is the ratio of the electromotive-forces developed in the armatures of the two machines. To do this we will consider separately the efficiencies of the three parts of the system. Writing E_1 for the electromotive-force developed in the generator, E_2 for that of the motor, r_1 and r_2 for their respective internal resistances, we shall then have

Efficiency of generator . . $\eta_1 = \dfrac{E_1C - r_1C^2}{E_1C}$;

Efficiency of line . . . . $\eta_2 = \dfrac{E_2C + r_2C^2}{E_1C - r_1C^2}$;

Efficiency of motor . . . . $\eta_3 = \dfrac{E_2C}{E_2C + r_2C^2}$;

Hence the resulting efficiency of the whole system will be

$$\eta = \eta_1 \times \eta_2 \times \eta_3 = \frac{E_2}{E_1}.$$

If the machines are shunt-wound or compound-wound, or if there is leakage on the line, the currents through the armatures will no longer be alike in the two machines. Writing the respective armature currents as i_1 and i_2, we shall have in this case, as the electrical efficiency of transmission,

$$\eta = \frac{E_2\,C_2}{E_1\,C_1}.$$

As an example of transmission to a moderate distance by continuous currents we may cite the plant at Schaffhausen erected by the Oerlikon Works of Zürich where 500 actual horse-power are delivered to the spinning mills electrically, with a nett efficiency of 78 per cent. from turbines in the river 750 yards away, two generators (6-pole over-compounded dynamos designed by C. E. L. Brown) being used to give each 330 amperes at 624 volts. The motors, which are of the same type, are constructed with field-magnets, which are relatively more powerful than those of the generators, and run without varying more than 3 per cent. in speed between no-load and full load. The commutators are guaranteed to last for 20,000 hours.

Another example[1] of transmission with continuous currents is afforded by the plant for supplying power to mills and to a central lighting station at Genoa. Water power derived from a tributary of the Po is converted for transmission in several stations on the mountain side at a distance of 16 miles from Genoa. In one of these stations there are eight Thury continuous-current machines of 70 H.P. each, coupled in pairs to 140 H.P. turbines. Each machine yields 47 amperes at 1000 volts. They are separately insulated on porcelain and coupled in series so that the power is transmitted at a total pressure of 8000 volts. The conductor is of bare copper carried on oil insulators.

When a very high electromotive-force is required for the purpose of transmitting power, it is found convenient to use alternating currents (p. 547) for the two following main reasons.

(1) Alternate-current generators require no commutator, and therefore the current can be generated by one machine at the full pressure required.

(2) Alternate currents can be transformed from one pressure to another by means of a simple transformer without moving parts.

The objections to alternate currents for this purpose are:—

(1) As the maximum pressure with alternate currents is 1·41 times the $\sqrt{\text{mean}^2}$ pressure, an alternate current of a certain value will not transmit as much power along a line as

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[1] *Elek. Zeitsch.* 1892, xiii. 216; *Journ. Inst. Elec. Eng.*, 1892. xxi. 534.

a continuous current of equivalent value whose pressure is equal to the maximum pressure of the alternate current.

(2) There may be a loss of *power* in the line due to the wattless current (p. 567).

(3) There is a certain amount of loss of *pressure* in the line due to self-induction apart from the resistance of the line (p. 559).

(4) There is a slight increase in the resistance of the mains due to skin effect if the frequency is high or the currents large (p. 578).

(5) Until recently alternate currents for transmitting power were open to the objection that alternate-current motors were not self-starting. This objection is removed by the introduction of self-starting monophase motors of high efficiency (p. 687), and by the employment of polyphase currents (p. 662).

The two advantages of alternate currents mentioned above so much outweigh the objections, that in the majority of cases of long-distance transmission in all parts of the world alternate currents are used.

In the largest scheme for the distribution of power ever undertaken, namely, from the Niagara Falls, alternate currents in two phases are used. The 5000 H.P. dynamos for generating the current are described on p. 638. They are three in number and yield 1550 amperes each (775 amperes in each circuit) at 2250 volts. The power is intended for distribution to factories in the immediate vicinity, and also for transmission to considerable distances. Continuous currents for aluminium smelting are obtained by means of rotating transformers. For distribution to great distances the pressure is raised by transformers to 20,000 volts. The water power available is about 100,000 H.P., and this will be utilized from time to time as the demand increases. It is probable that some of the future dynamos will generate the current for distant transmission at the full pressure without the intervention of step-up transformers. A subway carries the main conductors for a distance of 2500 feet, the conductors consisting of bare copper strip carried on oil insulators. From this subway branches are taken to neighboring factories.

An instance of transmission of power at high pressure which has been in existence for over three years is at Hochfelden, Switzerland, carried out by the Oerlikon Co. Fig. 511 gives a view of the station showing the three generators, which were designed by Mr. C. E. L. Brown, in 1890. They are 3-phase machines, each of 200 horse-power, running at 180 revolutions per minute. Excepting in having the vertical shafts directly above the turbines by which they are driven, they closely resemble the Lauffen generators. They give 86 volts pressure between the terminals. To raise the voltage each is connected to a 3-phase transformer immersed in oil, one of these transformers being visible on the right hand of the cut. The pressure is raised to 13,000 volts, at which pressure the currents are conveyed by three wires, each 4 mm. in diameter, to the Oerlikon Works (a distance of 24 kilometres, or about 15½ miles), where by means of step-down transformers of similar construction the pressure is lowered to 190 volts, and the currents are distributed for lighting and power at this pressure.

Graphic Representation of Transmission.—A convenient mode of representing graphically the relative amounts of energy expended at the transmitting end and utilized at the receiving end is the following, which is due to von Hefner Alteneck :—

Let (Fig. 512) the perpendicular lines A E_1 and B E_2 represent respectively the electromotive-forces at the transmitting and receiving machines ; and let the horizontal lengths A L_1, L_1 L_2, and L_2 B represent respectively the resistances of the machine at A, the line (including return wire), and of the machine at B. Join E_1 E_2 : the tangent of slope (E_1 F ÷ F E_2) of this line will represent the current flowing. From A and from B drop perpendiculars upon this sloping line, and produce them to the points W_1 and W_2, level with E_1 and E_2. The length of the lines E_1 W_1 and E_2 W_2 will represent relatively the energy transmitted and received. For, by the construction each is proportional to the respective electromotive-force and to the slope of E_1 E_2. The energy lost in heat may, on the same scale, be represented by the length of the line E_1 H.[1]

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[1] For a further geometrical discussion of the problem of electric transmission of power, see a paper by Reignier, in *La Lumière Électrique*, xxiii. 352, 1887.

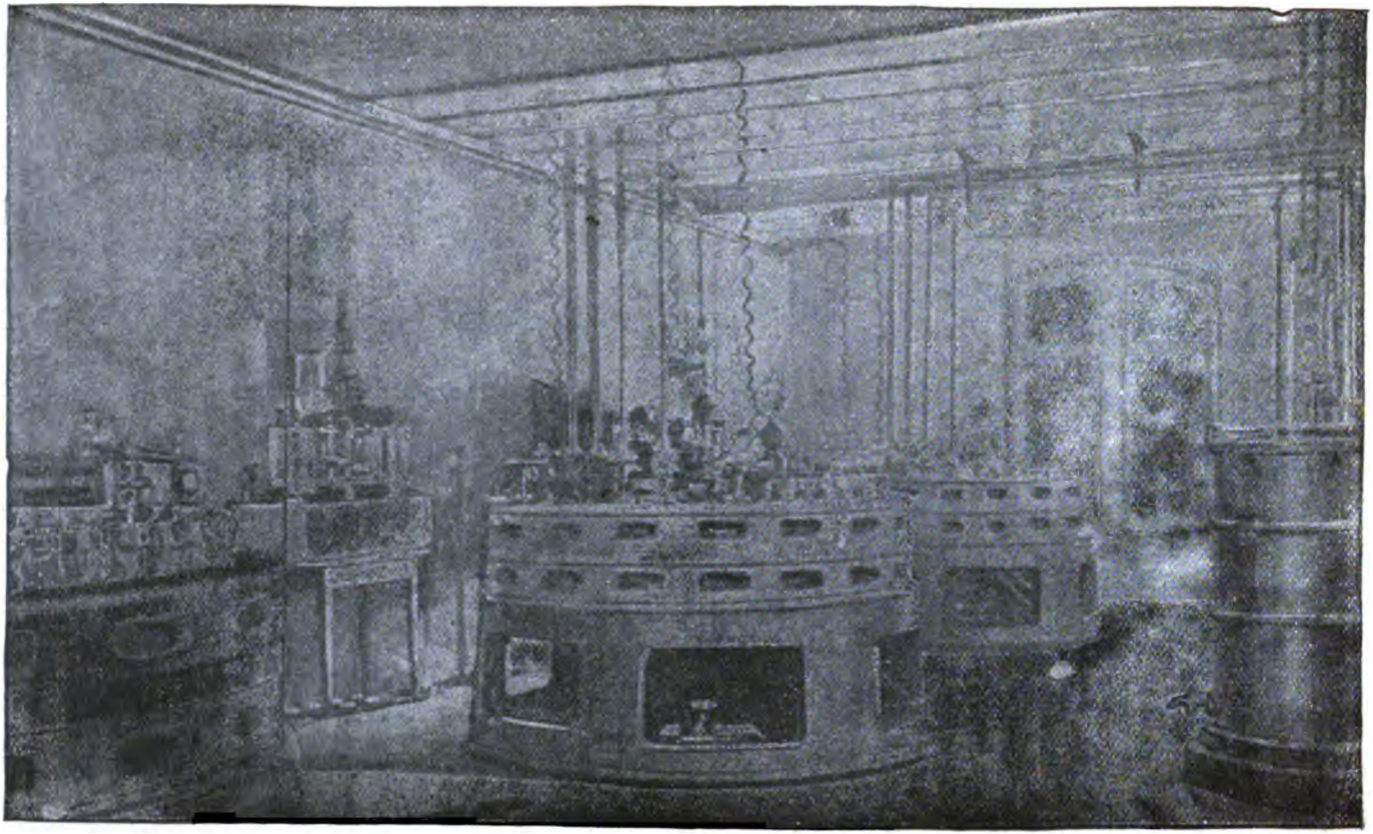

FIG. 44.—THREE-PHASE GENERATORS AT THE POWER STATION AT HOCHFELDEN (SWITZERLAND).

Economy of Transmission.—As already shown, the economy of transmission depends on the voltage at which the power is transmitted, and on the resistance of the line. The question then arises at what amount ought the latter to be fixed to make the economy a maximum. If one saves heat-waste by putting up a thick copper wire for the line, the interest on the prime cost of the line may more than balance the saving in power. An answer was given in 1881, by Lord Kelvin, to one form of the problem, in which it is assumed (1) that the voltage is fixed, (2) that the power to be transmitted is a fixed amount. If these are the conditions, then the total annual cost of the power wasted in the resistance of the line and of the interest on the copper (including insulation and erection) will be a minimum when these two annual items of cost are equal to one another. Much confusion has arisen from the ignorant application of Thomson's law to other cases than those for which it is true. In 1886, Professor Ayrton and Perry[1] considered some other cases, and have arrived at several important conclusions. If a given amount of power has to be furnished by a motor at one end of a line, using a given voltage at the generator at the other end, maximum economy is obtained, not by keeping the current-density constant, but by making it less, as the length of line to be used is greater. The smaller the voltage that may be employed at the generator, the smaller must the current-density in the line be to obtain the maximum efficiency. More recently, Mr. Kapp,[2] in his Cantor

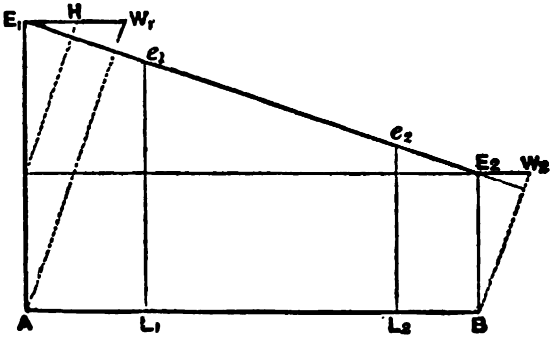

FIG. 512.

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[1] *Journal Soc. Telegr. Engineers*, xv. 120, 1886.

[2] *Journal Soc. Arts*, xxxix., July 10, 1891; also his book on *Electric Transmission of Energy*, 4th edition, 1894, in which some very useful curves are given.

Lectures, has given a more general solution, taking into account the voltage and the cost of the machines as well as that of the line. It is assumed that the annual value of power at the generating station is known as well as the cost of plant per horse-power. Of the data required to be known, such as primary horse-power, total efficiency, voltage at motor, annual cost of power delivered, and working current, the last mentioned is the most important to be calculated, for from it the other matters can then be found. Kapp finds that under no circumstances will it be economical to lose more than half the power in the line.

A useful set of tables, showing the cost of laying one additional ton of copper, meaning thereby that part of the capital outlay which is proportional to current, was given by Prof. G. Forbes in his Cantor Lectures[1] of 1885 on the Distribution of Electricity.

The secret of economy in all long-distance transmission lies, as we have seen, in the use of high voltage. But it is found in practice that continuous-current machines cannot advantageously be used at such high voltages as 3000 and 4000 volts, inasmuch as the commutators will not stand the strain on their insulation. Even putting several machines in series, though it lessens the voltage on each dynamo, does not prevent the risk of break-down of insulation. Hence the superiority of alternate-current apparatus, which requires no commutator. Moreover, where voltages exceeding 10,000 volts are desired, it is found preferable to use low-voltage alternators and motors, and to insert step-up transformers at the generating end, and step-down transformers at the receiving end (as proposed in 1881 by Deprez and Carpentier), since it is much easier to insulate thoroughly the stationary windings of a transformer than the parts of any running machinery. The question whether, of alternating systems, the ordinary single-phase, or one of the more novel 2- or 3-phase systems, is to be preferred in long-distance transmission is still an undecided matter.

As an example of long-distance transmission at an extra-high voltage may be cited the experimental line erected in the summer of 1891, from Lauffen to Frankfort, a distance of 175 kilometres. At Lauffen a special low-pressure turbine was fixed in the river Neckar to drive the 3-phase alternator, by Brown, described on p. 627, capable of giving (at full power) three alternating currents of about 1400 amperes each at 50 volts. These currents were converted by special transformers into three smaller currents at 8000, 12,500 or 25,000 volts. Three copper wires, each 4 mm. in diameter were carried to Frankfort on tall poles; about 10,000 porcelain insulators being employed, with oil-cups for high insulation. At Frankfort the currents were received into step-down transformers and reconverted to the low pressure of about 60 volts, to supply either lamps or 3-phase motors. Tests were made by a jury, having Prof. H. F. Weber as its head. Their report concludes with the following summary :—

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[1] *Journal Soc. Arts*, 1885.

(1) In the Lauffen-Frankfort plant for the electric transmission of energy over a distance of 170 kilometres, by means of a system of alternating currents, with a pressure of 8500 to 7500 volts, and bare copper conductors insulated by oil and porcelain, the lowest output in the tertiary circuit at Frankfort was 68·5 per cent., and the highest output was 75·2 per cent. of the energy given out by the turbine at Lauffen.

(2) In this transmission to a distance, the only cause of loss measurable by the instruments was that due to the resistance of the circuit (Joule's effect).

(3) Theoretical considerations showed that the influence of capacity upon long aerial bare conductors for transmission of energy to a distance by alternate currents, under the conditions employed, and with use of a frequency of 30 to 40 periods per second, is of so entirely subordinate a magnitude, that it need not be considered in designing electric transmissions.

(4) As the expression of our experience during the foregoing measurements for the determination of the efficiency of the Lauffen-Frankfort transmission of energy, we add, as a fourth result :—The electrical running with alternate currents of 7500 to 8500 volts in conductors of more than a hundred miles in length, insulated by means of oil, porcelain, and air, proceeds just as regularly, safely, and as free from disturbances as does running with alternate currents of a few hundred volts pressure over conducting wires of a few metres length.

In some further researches,[1] with a high pressure of 25,000 volts from line to line and with a frequency of 24 periods per second, an efficiency of 75 per cent. was obtained with a load of about 180 horse-power.

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[1] Official Report of the Frankfort Exhibition, ii. p. 451.

CHAPTER XXIX.

REGULATORS FOR DYNAMOS.

MODES of governing the performance of dynamos are needed, not only for keeping the pressure at some constant number of volts or for keeping current at some constant number of amperes, but also for such purposes as to enable the voltage of any one dynamo to be raised in order that it may feed into some distant point of a distributing network.

The output of a dynamo depends on three intrinsic matters, namely, (*i.*) speed n, (*ii.*) number of armature conductors Z, and (*iii.*) magnetic flux N ; and on two extrinsic matters, namely (*iv.*) resistance of the circuit ; and (*v.*) counter electromotive-forces in the circuit. It is therefore clear that any of these five matters might afford a method of controlling the performance of the machine.

To introduce resistances into the main circuit is always wasteful, and may be dismissed as an uneconomical method of regulation suitable only for experimental purposes. To introduce counter electromotive-forces into the external circuit can be done in the case of alternate currents by the use of choking coils, and in the case of continuous currents by the reversed introduction of charged secondary cells ; but this is impracticable save for special cases on the small scale. It remains therefore to consider the three intrinsic methods.

Speed governing is clearly limited to those cases where there is a separate engine for each dynamo ; and in such cases a special governor will be required instead of the usual centrifugal engine governor.

To alter the number of conductors in a rotating armature whilst it is running is absurd. Their *effective* number can, however, be altered by the device of shifting forward the brushes so that they collect the current not at the point of highest potential, but at some other point. This method virtually uses some of the armature windings, namely, those between the neutral point and the point to which the collecting brush is advanced, to produce internal counter electromotive-forces, To alter the magnetic flux is the almost universal mode of control; and it may be accomplished in two entirely distinct kinds of way. Since the flux depends on the excitation (or ampere-turns) and on the reluctance of the magnetic circuit, it can be varied by varying either the former or the latter. The excitation may be altered in various ways, (*a*) by the hand with the aid of rheostats and commutators in the exciting circuit, or (*b*) automatically by special governors in substitution for the hand, or (*c*) by devices of compound winding. The magnetic circuit may be varied in several ways, as (*d*) by moving the pole-pieces nearer to or further from the armature, (*e*) by opening or closing some other gap in the magnetic circuit, (*f*) by drawing the armature end-ways from between the pole-pieces, (*g*) by shunting some of the magnetic lines away from the armature by applying a magnetic shunt across the limbs. All these magnetic devices have been tried,[1] but not with much success except in small machines.

Hand-Regulators.—These consist of sets of sliding contacts to enable the operator to perform one of the following operations :—(1) Insert or remove resistance from the exciting circuit of a shunt dynamo by means of a rheostat[2] (see Edison's regulator, Fig. 152, p. 226); (2) insert or remove resistances, shunting the magnetizing coils of a series dynamo; (3) cut out more or fewer exciting coils, these being grouped in sections.

CONSTANT-PRESSURE AND CONSTANT-CURRENT REGULATORS.

In all automatic regulators there is a part which has to act as the brain of the instrument, watching as it were against any variation, and setting into action the mechanism which is to counteract the variation. This watching device is usually some sort of an electromagnet, often a coil with a movable plunger. When the volts are to be kept constant the coil of the controlling device must be wound as a voltmeter coil, that is of fine wire, of high resistance, and connected as a shunt. When the amperes are to be kept constant the controlling coil must be wound like an amperemeter with thick wire, of low resistance, and inserted in the main circuit. Alternators are usually regulated by operating on the circuit of their exciters, the current in the governor coil being derived from the mains by a small transformer.

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[1] For an example of (*d*) see Firth's method (see *Industries*, ix. 161) in which the polar masses are drawn backwards by screws; and of (*g*) a magnetic shunt applied by Desroziers, *La Lumière Électrique*, xxiv. 394. Other magnetic methods have been used by Goolden and Trotter, Langley, P. Müller, Lontin and Diehl.

[2] On the construction of such rheostats, choice of wires, and the like, see Herrick, *Electrical World*, xv. 240, 1890. Important advances have lately been made in the introduction of *enamelled* resistances, for the first of these operations. Fleming has devised special rheostats for absorbing power in wires strained over resilient supports.

Automatic regulators are of two species: in one the work of moving the regulator is accomplished mechanically, the control only being electrical; in the other both the control and the moving power are obtained electrically. Goolden's regulator, which was illustrated in the previous edition of this book, belongs to the former of these classes. The sliding piece of the rheostat is worked by a vertical screw, and this is caused to rotate right or left-handedly as may be required under the operation of a double crown-wheel on a sleeve on the vertical spindle to which rotation is imparted by a small pulley driven slowly from the engine. The controlling part—the brain of the apparatus—is a solenoid with suspended iron plunger. When the current in this coil is of proper normal strength the plunger is drawn in just so far that the crown-wheel is not in gear either with the upper or the lower driver. If the current in the coil grows weak the plunger rises, causing the crown-wheel to engage in the upper driving screw, which immediately begins to move the sliding-contact in such a way as to increase the excitation of the dynamo, and bring back the current in the coil to its normal strength. Slater Lewis has lately introduced a differential solenoid arrangement into the regulator.

An example of the second kind of regulator is that of Maquaire, in which the moving as well as the controlling mechanism is electrical. The moving mechanism is a small motor made reversible by the device explained on p. 519. The controlling mechanism is virtually a relay, consisting of an electromagnet with its armature balanced by a spring.

If the main pressure becomes too low the tongue of the governing relay rises, and touching one of the contact-stops, causes the motor armature to turn so as to alter the resistance and increase the excitation of the dynamo.

In Fig. 513 is shown an automatic regulator of the first kind, designed by Thury and manufactured by the Allgemeine Co., of Berlin. The vertical relay is shown on the left: it actuates one or other of two horizontal coils which throw into gear one or other of the two bevel wheels that drive the worm which turns the rheostat arm. The pulley on the end of the driving shaft must be driven slowly from the engine; or in emergency may be turned by hand.

A simple example of the purely electric regulator is afforded by that of Brush (Fig. 514) by which a series dynamo is made to yield a constant current. Across the field-magnets F. M. is connected a carbon shunt C of variable resistance, the resistance of the shunt being adjusted automatically by a governing electromagnet B whose coils form part of the main circuit.

When traversed by the normal current it attracts its armature A with a certain force just sufficient to keep it in its neutral position. If the current increases, the armature is drawn upwards and causes a lever to compress the column of carbon plates ; the current thus being diverted to a greater or lesser extent from the field-magnets. This regulator will keep the current constant even though the speed of driving may be irregular.

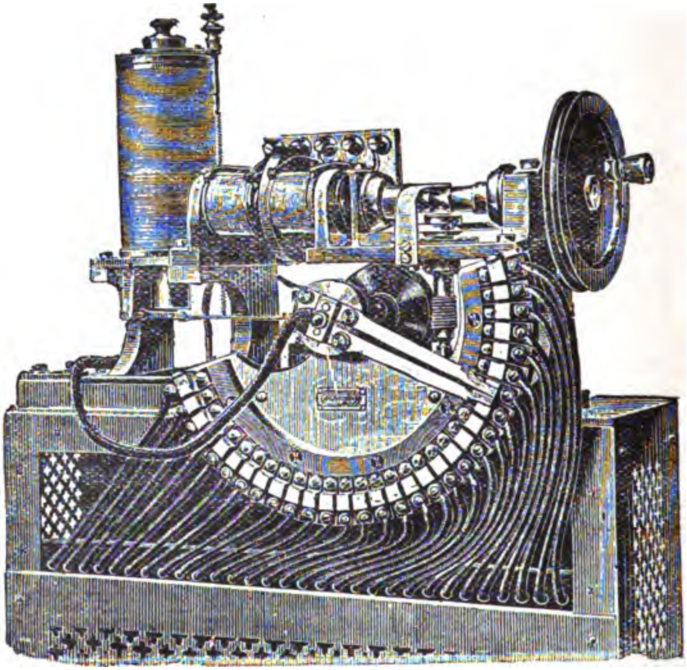

FIG. 513.—THURY'S REGULATOR.

Another purely electrical regulator is that used with the Thomson-Houston arc-light dynamo (p. 463).

In Statter's regulator the brushes are shifted by a motion derived mechanically from the rotation of the dynamo, but electrically controlled.

The method of regulating Parson's turbo-alternator was described on p. 625.

A regulator devised by Waterhouse employs a third brush upon the commutator to carry a variable portion of the current around a special circuit. It was illustrated in the previous edition of this book, as were also the regulators of Henrion and of Sperry.

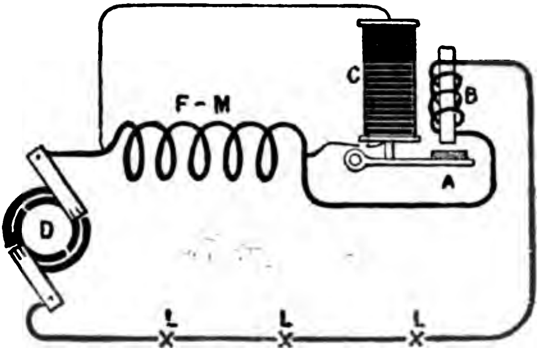

FIG. 514.—BRUSH'S AUTOMATIC REGULATOR.

A special study of this method of regulation has been made by Caldwell,[1] who has shown that it can also be applied to constant-pressure regulation.

For constant-current work Wood has devised a regulator in which a pilot brush is also employed, but there are two exciting circuits wound differentially, and there is an electromechanical device for shifting the brushes, attached to the dynamo. It was depicted in the former edition.

An interesting example of the use of a magnetic shunt to produce a constant current, occurs in the regulator of Trotter[2] and Ravenshaw, in which, instead of diverting the magnetic lines out of their usual path, into a path of lower magnetic reluctance by employing a movable keeper of iron, the plan is adopted of fixing the keeper and varying its effects by surrounding it with a counter magnetizing coil.

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[1] *Electrician*, xxii. 217, 1888; and remarks by Professor Nicholls, *ibid.*, 441, 1889.

[2] See paper by A. P. Trotter, in *Electrician*, xix. 374, 1887. A drawing of the governor itself is given in the *Electrical Review*, xix. 289, Sept. 17, 1886.

M. Reignier[1] has drawn attention to a solution of the problem of exact governing to procure a constant current by automatically varying the number of coils through which the current is permitted to pass.

ELECTRIC GOVERNORS FOR STEAM-ENGINES.

No centrifugal governor attached to the steam-engine can keep the speed of the dynamo truly constant; for it does not act until the speed has become either a little greater or a little less than the normal value. Few mechanical governors will keep the speed within 5 per cent. of its proper value, under sudden changes of load. Hence the suggestion which underlies all electrical governors, that the admission of steam from the boiler to the engine should be controlled by the electric current itself, the speed of driving being varied according to the demands of the circuit. It is emphatically needed wherever the loads are liable to sudden variations, as in the case of generators for electric railways. Numerous suggestions of a more or less practical nature have been made by Lane-Fox, Andrews, Richardson and others.

Richardson's governor[2] was described in detail and illustrated in the previous edition of this book. More recently Mr. Richardson has described[3] some detail modifications which include the use of a relay controlling a mechanically driven governor so as to regulate the engine to maintain a constant electric pressure at any given distant point in the network of mains.

Willans' governor[4] employs the attraction exerted by a solenoid on an iron core to actuate an equilibrium valve; but the action is indirect, the solenoid core operating on the small valve which controls a hydraulic piston, the latter in turn controlling the large steam valve. The arrangement was depicted and described in the previous edition of the present book. A comparatively small solenoid, actuated by but 0·3 ampere of current and absorbing only about 32 watts of power, may by this use of a hydraulic relay, or by a steam relay valve, bring a force of many pounds to bear upon the main steam valve, and will control with ease an engine of several hundred horse-power.

One great advantage of the electric governor is that it cuts down the consumption of steam to the actual demands made upon the electric circuit, and prevents injury both to the dynamo and to the steam-engine.

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[1] *La Lumière Electrique*, xxvi. 420, 1887.

[2] See Specification of Patent, No. 288 of 1881.

[3] *Proc. Inst. Civil Engineers*, cxx. pt. ii., 1895.

[4] See Specifications of Patent Nos. 1184, 5291 and 5945 of 1883; also paper by P. W. Willans in *Proc. Inst. Civil Engineers*, lxxxi. pt. iii. 1884–5.

Dynamometric Governing.— Another method of governing dynamos is too important to be omitted. The power transmitted along a shaft is the product of two factors, speed and torque.

But the power of a dynamo is measured electrically by the product of its electromotive-force into the current it drives through the circuit. If E stands for the electromotive-force, and C for the current, then

$$E\,C = \text{power (in watts)}.$$

Now we know that, other things being equal, the electromotive-force E of the dynamo is proportional to speed of driving. It follows at once that *the torque will be proportional to the current* C. This at once suggests that a dynamo may be driven so as to give a constant current, provided it be driven from a steam-engine governed *not by a centrifugal governor to maintain a constant speed, but by a dynamometric governor to maintain a constant torque or turning moment.* Some good transmission dynamometers, such as that of Morin, or one of the later varieties, such as those designed by Ayrton and Perry, or best of all that designed by the Rev. F. J. Smith,[1] may be adapted to work an equilibrium valve, and would fulfil the above condition of governing.

Prof. E. Thomson has suggested the use of a dynamometric apparatus to govern a constant-current dynamo by the method of shifting the brushes. A description of this governor was given in the second edition of this work.

Governing by Steam-pressure.—It was remarked above that electric power and mechanical power are each a product of two factors. But in an ordinary steam-engine the work per second also consists of two factors, viz. speed of piston and steam-pressure ; and the angular velocity of the shaft is proportional to the former, and its transmitted torque to the latter. Therefore the condition of maintaining a constant current ought to be fulfilled if the pressure is always constant. If the valves are such as to admit a fixed quantity of steam at each stroke, and if the boiler pressure is really kept up, then the average pressure behind the piston ought to be constant. In practice this is never attained, on account of the friction of the steam against the steam-pipes and port-holes of the valves. The internal friction in the engine plays the same part in preventing absolutely true self-regulation, as does the internal electrical resistance in the dynamo. An approximation is all that is possible.[1] In an experiment made by M. Pollard with a Gramme dynamo, the current gave deflections on a galvanometer, varying only from 52° to 54°, while additional resistances were introduced into the circuit, which caused the speed to run up from 436 to 726 revolutions per minute. Theoretically, therefore, a constant current ought to be one of the easiest things to maintain with a series dynamo. Have adequate boilers, keep the steam-pressure always at one point, abandon all governors, and admit equal quantities of steam at each stroke whatever the speed; the result *ought* to be a constant current. The condition of maintaining a constant potential cannot be similarly solved, except by employing a shunt dynamo under conditions that are both uneconomical and impracticable. But in the case of constant-current working it is possible to go further toward realizing such results. The existing method of maintaining a constant steam-pressure is to put upon the boiler a pressure-gauge which indicates to the stoker when he is to add more fuel and when to damp down the fire. Let the pressure-gauge be abandoned, and instead, let there be provided at the side of the furnace an amperemeter, and let the stoker feed or damp his furnace fires according to the requirements of the electric system of distribution. Is there any valid reason why such a method of government should not be efficient in practice, at least in the case of the series dynamo for constant currents?

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[1] See his excellent little book on *Work-measuring Machines*, published by Messrs. E. and F. N. Spon.

Finally, to render the system truly automatic, it is conceivable that mechanical stoking appliances might be arranged, under the control of the amperemeter or voltmeter, to supply the fuel in proportion to the number of lamps alight. In the case of gas engines or oil engines such a control would be very easily carried out.

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[1] See Edmunds in *Journal Soc. Teleg. Engineers*, xvii. 697, 1888; also *Electrician*, xxii. 349, 422, 1889.

CHAPTER XXX.

TESTING DYNAMOS AND MOTORS.

TESTS to be applied to dynamos are of two kinds, viz. those which relate to the resistance and insulation of the various parts, and those which relate to the efficiency under various loads.

Testing Construction.—The resistance of the various parts of the armature coils, of the field-magnet coils, and of the various connections, may be tested in the ordinary manner, by means of a Wheatstone's bridge. The only point of difficulty lies in measuring such small resistances as those of armatures and of series coils, which are often very small fractions of an ohm. In this case probably the best method of proceeding is the following. By means of a few accumulator cells send a strong current through the coil or armature whose resistance is to be measured, interposing in the circuit an amperemeter. While this current is passing, measure, by means of a sensitive voltmeter, the fall of potential between the two ends of the coil. By Ohm's law, the number of volts of fall of potential divided by the number of amperes will give the resistance in ohms. Additional accuracy may be secured by connecting in the circuit a strip of stout German silver, as recommended by Lord Rayleigh, of known resistance, and comparing the fall of potential between the two ends of the strip with the fall of potential in the coil. The ratio of the two falls of potential will equal the ratio of the resistances.

The internal resistance of a dynamo when warm after working for a few hours is considerably higher than when it is cold. Tests of resistance ought therefore to be made both before and after the dynamo has been running. The perfection of the magnetic circuit may be tested in two ways. One way is to measure the proportion of magnetic leakage inductively (p. 153). The other way is to join up a known suitable resistance to the terminals of the machine, and then to run it slowly, gradually increasing the speed until it excites itself. (The method is of course inapplicable to many alternate-current machines.) The least speed of self-excitation is, *cœteris paribus*, a measure of the goodness of the magnetic circuit.

Testing Insulation-resistance. — The rational mode of testing the insulation in the workshop is to apply a high voltage—say from 2000 to 4000 volts—and see whether the insulation resists being pierced. The electric tension or stress to which the dielectric is subjected, tending to pierce it, varies as the square of the volts. The most convenient way of applying the test is to use a small alternate-current transformer giving the requisite voltage. All dynamos, motors and transformers intended for high voltage work should be tested at double the volts which they are intended to work at. Tests of the insulation-resistance between the coils of a dynamo and its metal cores or frame by use of a Wheatstone's bridge, made regularly day by day, are only useful as far as they serve as a guide to the way in which the machine is being cared for; since damp and dirt lower the insulation, and if neglected promote likelihood of a break-down.

Testing Temperature-rise.—The instructions given by the Admiralty for tests of temperature are as follows:—

At the end of six hours' trial, and one minute after stopping the machine, no accessible part of the armature or field-magnet must have a temperature of more than 30° Fahr. above that of the dynamo room, taken on the side of the dynamo remote from the engine, and three feet distant from it. Also the maximum temperature of the armature at the end of the six hours' trial must not exceed the temperature of the dynamo room by more than 70° Fahr." It is usual to employ thermometers with narrow cylindrical bulbs which can be inserted in the armature, or laid upon it and covered with a pad of cotton wool while the test is made.

Testing Performance and Efficiency.—The testing of the efficiency and working capacity of a dynamo, whether working as generator or as motor, is a more serious matter, and involves both electrical and mechanical measurements.

In the case of the dynamo generating currents, measurements must be made (*a*) of the mechanical input and (*b*) of the electrical output.

In the case of the motor doing work, measurements must be made (*a*) of the electrical input, and (*b*) of the mechanical output.

Measurement of Power.—The general methods of measuring the power mechanically are as follows:

(*a.*) *Indicator Method.*—By taking indicator diagrams from the steam-engine which supplies the power.

(*b.*) *Brake Method.*—By absorbing the power delivered by the machine, at a friction brake such as that of Prony, Poncelet, Appold, Raffard, or Froude.

(*c.*) *Dynamometer Method.*—By measuring in a transmission dynamometer or ergometer, such as that of Morin, von Hefner-Alteneck, Ayrton and Perry, or of F. J. Smith, the actual mechanical power of the shaft or belt.

(*d.*) *Balance Method.*—By balancing the dynamo or motor on its own pivots and making it into its own ergometer.

(*e.*) *Electrical Method.*—By making the motor drive the dynamo which supplies it, measuring electrically the work given out in the one, or absorbed by the other, and then measuring, either mechanically or electrically, the difference.

(*f.*) *Steam Consumption.*—In cases where indicators cannot be used (as for example in tests of steam turbines), the weight of steam consumed per hour, as measured by feed-water supplied to the boiler or by the water from the condenser, may be taken as a measure of the gross power.

(*a.*) *Indicator Method.*—The operation of taking an indicator diagram of the work of a steam-engine is too well known to engineers to need more than a passing reference. It measures the gross power imparted thermally to the engine, not the nett power given by the engine to the dynamo. This method is, however, not always applicable, for in many cases the steam-engine has to drive other machinery, and heavy shafting for other machinery. In such cases the only remedy is to take two sets of indicator diagrams, one when the dynamo is at work, the other when the dynamo is thrown out of gear, the difference being assumed to represent the horse-power absorbed by the dynamo.

(*b.*) *Brake Method.*—The friction brake of Prony is well known to engineers, but the same can hardly be said of the more recent forms of friction dynamometers. Various improvements have been introduced in detail from time to time by Poncelet, Appold, and Deprez. In Prony's method the work is measured by clamping a pair of wooden jaws round a pulley on the shaft; the torque on the jaws being measured directly by hanging weights on a projecting arm with a sufficient moment to prevent rotation. If p is the weight which at a distance l from the centre balances the tendency to turn, then the friction force f multiplied by the radius r of the pulley will equal p multiplied by l.

This may be written,

$$\text{Torque} = f\,r = p\,l.$$

From which it follows that

$$f = \frac{p\,l}{r}.$$

If n be the number of revolutions *per second*, then $2\,\pi\,n$ is the number of radians per second, or in other words, the angular velocity, for which we use the symbol ω, and $2\,\pi\,n\,r$ is the linear velocity v at the circumference. Now the work per second, or power, is the product of the force at the circumference into the volocity at the circumference, or

$$w = f\,v = \frac{p\,l}{r} . \, 2\,\pi\,n\,r = 2\,\pi\,n\,p\,l.$$

If p is measured in pounds' weight, and l in feet, then, remembering that 550 foot-pounds per second go to one horse-power, we have,

$$\text{horse-power absorbed} = \frac{2\,\pi\,n\,p\,l}{550};$$

or, if p is expressed in grammes' weight, and l in centimetres, it must be divided by $7{\cdot}6 \times 10^6$ to bring it to horse-power.

The latter improvements imported into the Prony brake are of great importance. Poncelet added a rigid rod at right angles to the lever, and attached the weights at the lower end. Appold, substituted for the wooden jaws a steel strap, giving a more equable friction, and therefore having less tendency to vibration. Raffard[1] substituted a belt differing in breadth, and therefore offering a variable coefficient of friction, according to the amount wrapped round the pulley. Further modifications of this kind of brake dynamometer have been made by Professor James Thomson, Professor Unwin, M. Carpentier, and by Professors Ayrton and Perry. The friction of a turbine wheel was also applied as a dynamometer brake by the late W. Froude. Professor Alex. B. W. Kennedy has obtained excellent results from the use of a rope brake.

As all these brake dynamometers measure the work by destroying it, it will be seen that though they are admirably adapted to measure the work furnished by a motor, they cannot, except indirectly, be applied to measure the work supplied to a dynamo. Some experience in working with these machines is essential if reliable results are to be obtained; but with the more modern forms of instruments, such as those of Poncelet and Raffard, the results are very good. The great secret of success is to keep the friction surfaces well lubricated with an abundant supply of soap and water.

Probably the most accurate method of measuring power by absorbing it is to use as brake a dynamo of high and known efficiency on a load of lamps, the output being measured by amperemeter and voltmeter.

(*c.*) *Dynamometer Method.*—The Prony brake was styled above a brake dynamometer; but the true dynamometer for measuring transmitted power does not destroy the power which it measures. Transmission dynamometers may be divided into two closely allied categories: those which measure the power transmitted along a belt, and those which measure power transmitted by a shaft.

In the case of transmitting power by a belt, the actual force which drives is the difference between the pull in the two parts of the belt. If F′ is the pull in the slack part of the belt before reaching the driven pulley, and F the pull in the tight part of the belt after leaving the driven pulley, then F — F′ represents the nett pull at the circumference, and $(F - F') \times r$ is the torque T. Then if n is the number of revolutions *per second* the angular velocity ω will be equal to $2 \pi n$. This gives us as the work per second, or power,

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[1] For further accounts of these instruments the reader is referred to Weisbach's *Mechanics of Engineering*; Spons' *Dictionary of Engineering*, Article "Dynamometer"; Smith's *Work-measuring Machines*; a series of articles in the *Electrician*, 1883–4, by Mr. Gisbert Kapp; *Proc. Inst. Mech. Eng.*, 1877, p. 237 (Mr. Froude); *Rep. Brit. Assoc.*, 1883 (Prof. Unwin); *Journ. Soc. Telegr.-Eng. and Electr.*, vol. xii. p. 346 (Profs. Ayrton and Perry). See also *Official Report* of the Electrotechnical Exhibition of Frankfort, 1891, for the brake tests made on the turbines at Lauffen.

$$w = \omega T = f v = 2 \pi n r (F - F').$$

As before, if F is expressed in pounds' weight and r in feet, the expression must be divided by 550 to bring to horse-power; or must be divided by $7 \cdot 6 \times 10^6$ if the quantities are expressed in grammes' weight and centimetres.

A dynamometer which can be applied to a driving belt, and actually measures the difference $F - F'$ in the tight and slack parts of the belt, has been designed by von Hefner Alteneck, and is commonly known as Siemens' belt dynamometer.[1] Other forms have been devised by Sir F. J. Bramwell, W. P. Tatham,[2] W. Froude, T. A. Edison and others. Nearly all of these instruments introduce additional pulleys into the transmitting system, causing additional friction.

Much more satisfactory are those transmission dynamometers which measure the power transmitted by a shaft. In nearly all instruments of this class there is a fixed pulley keyed to the shaft, and beside it a loose pulley connected with it by some kind of spring arrangement, so set that the elongation or bending of the spring measures the angular advance of the one pulley relatively to the other; this angular advance is proportional to the transmitted torque. To this class of instrument belongs the well-known dynamometer of Morin, in which the displacement of the loose pulley is resisted by a straight bar spring, the centre of which is attached to the driving shaft. Modifications of the Morin instrument have been devised by Easton and Anderson, Heinrichs,[3] Ayrton and Perry,[4] Murray,[5] and the Rev. F. J. Smith, of the Millard Engineering Laboratory, Oxford. Of the last named instrument, a full description and cut were given in former editions of this book.

(*d.*) *Balance Method.*—With small motors there arises the difficulty that the ordinary means of measuring the work they perform introduce relatively large amounts of extraneous friction. The motor to be tested is placed with its armature spindle between centres, or on friction wheels, and the weight of the field-magnets and frame is very carefully balanced with counterpoise weights. In Fig. 515, B D represents the field-magnets and frame of the motor duly counterpoised, and E is the armature. When the current is turned on, the armature tends to rotate in one direction and the field-magnets in the other; the angular reaction being of course equal to the angular action. If the reaction which tends to drive the field-magnets round be balanced by applying a force P (for example that of a spring balance) at the point C of the frame A B C D, then the moment of this force, P *d*, measures the torque, exactly as in the Prony brake. Hence it will be seen that the motor has become its own dynamometer, the magnetic friction between the armature and the field-magnet being substituted for the mechanical friction between the pulley and the jaws. A modification of the balance method, due to Herman Müller, consists in swinging the dynamo in a cradle, pendulum fashion, from the driving shaft, and estimating the power absorbed by the displacement from the vertical line.

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[1] One form of the Siemens dynamometer is described by Hopkinson, *Proc. Inst. Mechan. Eng.*, 1879. A more modern form is described by Schroter, *Bayerisches Industrie-und Gewerbeblatt*, 1883.

[2] *Journ. Franklin Institute*, Nov. 1886.

[3] See *Engineering*, May 2, 1884, and *Electrical Review*, April 26, 1884.

[4] *Journ. Soc. Telegr.-Eng. and Electr.*, xii. 163, 1883. [5] *Ibid.*, xviii. 1889.

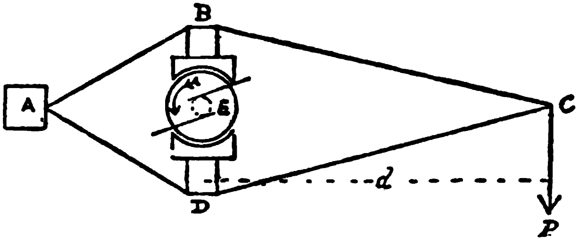

FIG. 515.—REV. F. J. SMITH'S METHOD OF TESTING MOTORS.

M. Marcel Deprez and Professor C. F. Brackett have proposed to apply the balance method to dynamos in action. Professor Brackett places the dynamo in a sort of cradle, balanced on centres that lie in the axis of rotation, and measures the torque between the armature and field-magnets, and multiplying this by the angular velocity $2 \pi n$, obtains the value of the power transmitted to the armature.

All these several dynamometric methods necessitate the use of a speed-indicator to count the number of revolutions n, which enters as a factor into the calculation of horse-power. The number of revolutions *per second* n being known, the angular velocity ω — $2 \pi n$ can be calculated. This only requires to be multiplied by the torque $T = F r$ give the power or work-per-second w. And if T is expressed in pound-feet, then,

$$\text{horse-power} = \frac{2 \pi n F r}{550} = \frac{\omega T}{550}.$$

(*e.*) *Electrical Methods.*—There are several varieties of this modern method of testing, and they involve the use of two or in some cases three machines. Two machines, one to act as generator, the other as motor, are connected together both electrically and mechanically, so that the power is *circulated* between the two machines, passing from generator to motor electrically, and returned from motor to generator mechanically. The power given out by the generator machine, and that absorbed by the motor, are measured electrically. In the original plan of Dr. J. and E. Hopkinson,[1] the small additional power required to drive the generator was supplied by a steam-engine and measured mechanically by a dynamometer. By thus circulating the power it is possible to test a pair of machines at say 500 horse-power each, using only a 50 horse-power steam-engine. Modifications of this method for the purpose of obviating all mechanical measurements have been suggested by Lord Rayleigh,[2] Major Cardew,[3] whose method dates from 1882, M. Menges,[4] Mr. Ravenshaw[5] and Mr. Swinburne.

All these methods are far more accurate than the rough mechanical methods of earlier date, and each has its advantages, but Hopkinson's method requires two similar machines, and Cardew's requires three machines, one of which must be powerful enough to run the other two. In Swinburne's method the loss of power due to resistance of conductors is calculated, and this deducted from the whole loss of power in the machine gives the "stray power" made up of losses due to eddy-currents, friction and magnetic hysteresis, which are thus measured together. This stray power is determined by using the machine as a motor, the field-magnets being separately excited so that the armature has the same magnetic induction as at full load, the electromotive-force applied to it being such as to drive it at its normal speed. Only a small generating dynamo is required to furnish the current for this. When matters are so arranged that the machine to be tested runs at its normal speed, the power used in driving the machines (which is measured electrically by taking readings of the volts on the armature and the amperes flowing through it, and multiplying up) is equal to the stray power at full load.

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[1] *Phil. Trans.*, 1886, ii. 347. See also *Electrician*, xvi. 347, 1886; and *Electrical Review*, xviii. 207 and 230, 1886.

[2] *Electrical Review*, xviii. 242, 1886.

[3] *Ibid.*, xix. 464, 1886; and *Electrician*, xvii. 410, 1886; and xxi. 275, 1887.

[4] *Electrician*, xvi. 371, 1886.

[5] *Electrical Review*, xix. 424 and 437, 1886.

[6] *Ibid* xxi., 181 and 215, 1887.

An example may be useful. Suppose we have to test a large 50 kilowatt shunt-wound dynamo, giving 500 amperes at 100 volts at 720 revolutions per minute, and that $r_a = 0{\cdot}006$ ohm, and $r_s = 12$ ohms, the lost amperes will be $100 \div 12 = 8{\cdot}5$, total current say 508 amperes; hence lost volts $508 \times 0{\cdot}006 = 3$ volts; whence $E = 103$ volts. Watts lost in armature $= 508 \times 508 \times 0{\cdot}006 = 1548$. Watts lost in shunt coil $= 100 \times 100 \div 12 = 833$. Now arrange any small dynamo, of say 2 H.P., to give out current at 103 volts; and from this run the large dynamo that is to be tested, as a motor, with no other load than its own friction, hysteresis and eddy-currents. It will run under 720 revolutions, since with such small current its armature produces no demagnetizing action to quicken it up. Therefore add some resistance to its shunt till it comes up to speed. Then measure the current it is taking; this multiplied by E gives the stray power. Suppose it takes 9 amperes, then the stray power is $103 \times 9 = 927$ watts. We may at once reckon out the efficiencies. The losses now known are $1548 + 833 + 927 = 3308$. Add this to the 50,000 watts of nett output, and we get the gross output 53,308. Hence we have the following :—

$$\text{Gross efficiency} = \frac{52381}{53308} = 98{\cdot}3 \text{ per cent.}$$

$$\text{Electrical efficiency} = \frac{50000}{52381} = 95{\cdot}5 \quad \text{“}$$

$$\text{Nett efficiency} = \frac{50000}{53308} = 93{\cdot}8 \quad \text{“}$$

Mr. Kapp [1] has devised a method of testing which permits the commercial or nett efficiency to be determined electrically with far higher accuracy than is possible with any mechanical dynamometer. It requires two machines of nearly equal power, one G to run as generator, the other M as motor, together with a small auxiliary machine X of normal voltage, to which the other two are coupled in parallel, Fig. 516. The armatures of G and M must also be coupled together mechanically, and the field of M must be weakened by use of a rheostat, so that it may run as a motor. X gives the current necessary for exciting and for making up the difference between the currents in G and M. Insert an amperemeter from one brush of G to one of M to measure the current. Take a reading of the G current when the auxiliary current is led in on the right, and another reading of the M current when the auxiliary current is led to the left. As the volts are the same in each case, the ratio of the two currents is the efficiency of the combination of the two machines; and the square root of the ratio of the two readings is the efficiency of either machine.

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[1] See *Electrical Engineer*, Jan. 22, 1892, and *Electrician*, July 5, 1895, 319.

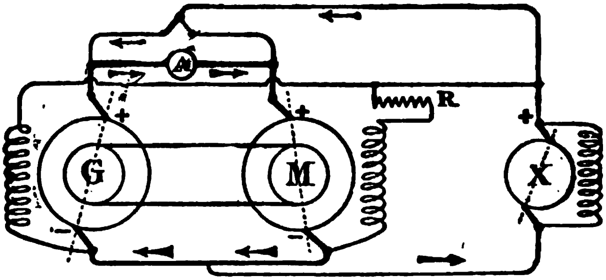

FIG. 516.—KAPP'S METHOD OF TESTING EFFICIENCY.

Testing Separate Losses.—In the preceding paragraph no distinction was made between the three sources of loss which go to make up the stray power, namely, friction, eddy-currents and hysteresis. It was indeed possible to separate the eddy-current loss from the others by making experiments at different speeds,[1] because the eddy-current loss increases proportionately to the square of the speed, whilst the other losses are approximately proportional simply to the speed. The power thus wasted was given to the armature by a motor and measured electrically. In 1891, a method of separating these losses was independently published by Kapp[2] and by Housman.[1] From the latter's paper is taken Fig. 517, which shows the method adopted by both these engineers. The method is as follows :—Let the field-magnet be separately excited to a constant value. Then measure the currents required to run the armature as a motor with no load at different speeds, by using different volts. The results when plotted out as a curve give a straight line A B, Fig. 517, cutting the axis of current above the origin. A horizontal line A D, through A, divides the ordinates, such as C B, into two parts; one C D, which represents the losses that are proportional to speed; and another D B which represents those that are proportional to the square of the speed. To separate friction of bearings and brushes, the armature should be coupled direct to another similar machine, the latter running without excitation of magnets, when the increase of current needed to drive will give a measure of frictional loss, and from this the lines E F and G H may be plotted out. If a second set of observations are made with a field of different strength, a second line A′ B′ will be obtained, which will be above or

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[1] *Journ. Inst. Electrical Engineers*, xviii. 620, 1889.
[2] *The Electrician*, xxvi. 699, 1891.

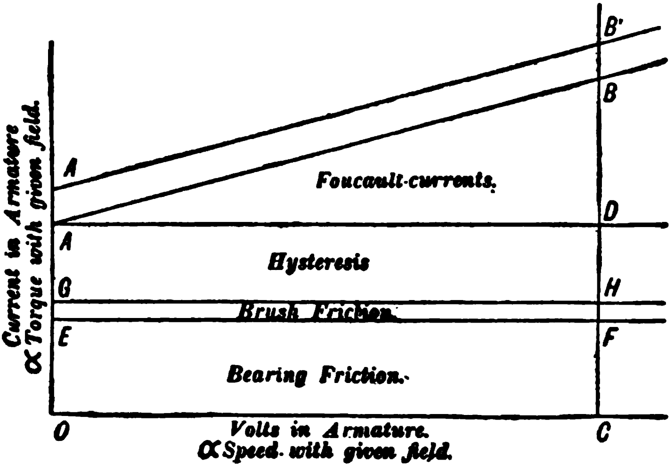

FIG. 517.—SEPARATION OF LOSSES IN DYNAMO.

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[1] *Ibid.*, xxvi. 700, 1891; also *Journ. Inst. Electrical Engineers*, xx. 298, 1891.

below A B, according to whether the change of field has increased or diminished the total losses. The minimum total loss usually occurs with an excitation that makes the flux-density B in the armature about 15,000 or 16,000; for when the excitation is pushed further, not only does hysteresis become much greater, but the eddy-currents in shaft and pulley due to the leakage of magnetic lines are greater. If the line A B curves upwards at the higher values, it shows that the eddy-currents in the armature are producing perceptible demagnetization.

Testing of Combined Plant.—It is usual to specify for combined plant that the efficiency of the combined engine and dynamo taken together, on a run of several hours at full load, shall reach some prescribed figure; and that the steam consumption per kilowatt-hour of output shall also not exceed a given limit. The requirements of British consulting engineers have been for many years exacting, with the result that manufacturers and contractors[1] have attained to exceedingly high efficiencies.

As an example of tests of a continuous-current combined plant we may take those made by Professor A. B. W. Kennedy in May 1893, at Thames Ditton, of a 123 kilowatt shunt-wound dynamo by Holmes & Co., direct driven from a two-crank compound Willans engine (condensing) at 335 revolutions per minute. During a six hours' run with a load of 1010 amperes at 120 volts (or 121·5 kilowatts, or 162·8 horse-power electrical output), steam was being used at 3314 lbs. per hour, or 27·3 lbs. per kilowatt hour, or 20·3 lbs. per horse-power hour, of the nett electrical output. The internal horse-power during same time, as measured with indicators, was 190·2, giving an efficiency of 85·6 per cent. The steam used per horse-power indicated was 17·4 lbs. The rise of temperature at the end of the run was found to be 40° C. above that of the surrounding air. Tests were made also at $\frac{1}{4}$, $\frac{1}{2}$ and $\frac{3}{4}$ load, also when the dynamo was run on open circuit, excited and unexcited, and when the engine was run alone uncoupled.

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[1] See a remarkable paper by Mr. R. E. Crompton, *Proc. Inst. Civil Engineers*, vol. cvi. 1891.

The results are plotted out in the accompanying diagram, Fig. 518. When worked out in detail it appears from these tests that the efficiency of the engine by itself is 89·5 per cent.; that of the dynamo by itself 95·6 per cent.

The elaborate tests of Parsons' steam turbine (p. 625), made by Professor Ewing in 1892 showed a steam consumption of 27 to 28 lbs. per kilowatt hour at full load, and of 30 to 32 lbs. per kilowatt hour at half load; still higher results being claimed for the recent steam turbines of larger size.

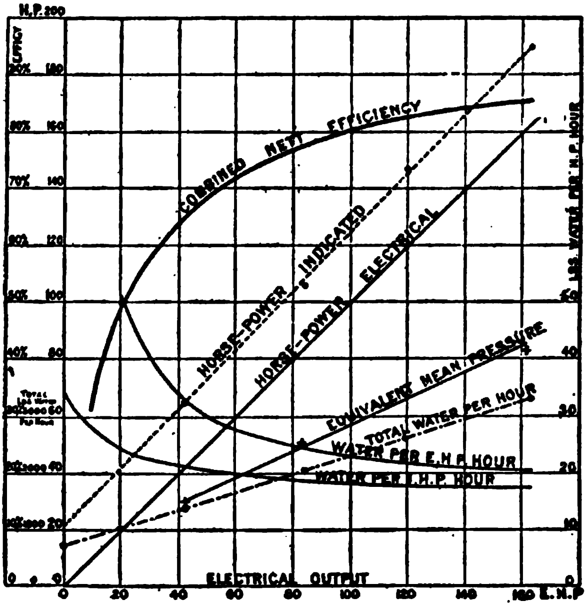

FIG. 518.—TEST OF HOLMES-WILLANS COMBINED PLANT (KENNEDY).

An elaborate arrangement of speed-cones for dynamo-testing, designed by Prof. Ayrton, is described in *Industries*, June 22, 1888. For detailed accounts of tests on dynamos the reader is referred to the following sources:—*Report of Committee of Franklin Institution*, 1878; *Official Report of Munich Electric Exhibition*, 1882; also Prof. W. G. Adams' Inaugural Address, *Journal of Society of Telegraph-Engineers and Electricians*, xiv. 4, 1885; also Reports of Electrical Exhibition at Philadelphia, 1884, published in *Journal of the Franklin Institution*, 1885; tests of arc-lighting dynamos at Melbourne Exhibition, by

K. L. Murray, *Journal Institution Electrical Engineers*, xviii., 1889; tests of dynamos (Desroziers, Edison, Gramme, &c.) at Paris Exhibition of 1889, by A. Minet, *La Lumière Électrique*, xxxv. 1889; tests on Stanley Arc Alternator by Duncan and Hassen, *Electrician*, xxvi., Jan. 1891; tests of a Goolden dynamo and Willans engine, separating the losses, *ib.* xxvi. p. 86, 1890; tests of a Wenström dynamo, separating the losses, by Duncan, *Electrical Review*, xxvi. 116, Jan. 1890; papers on Causes of Losses, by Hummel, in *Elektrotechnische Zeitschrift*, viii. 1887, and xii. 1891. At the Frankfort Exhibition of 1891, very careful tests were made of numerous machines under very favorable conditions. These are detailed in the second volume of the *Official Report*, published at Frankfort in 1893.

CHAPTER XXXI.

MANAGEMENT OF DYNAMOS.

THIS chapter is devoted to three topics :—(1) The coupling of two or more dynamos. (2) General instructions in use of dynamos. (3) The diseases of dynamos.

ON COUPLING TWO OR MORE DYNAMOS IN ONE CIRCUIT.

It is sometimes needful to couple two or more dynamos together so that they may supply to a circuit a larger quantity of electric energy than either could do singly. Thus it may occur that two dynamos, neither of which can safely carry a greater current than 1000 amperes, are required to supply jointly a 2000-ampere current: or two machines, each of which can run at 60 volts, are required to furnish an electromotive-force of 120 volts. Simple as these cases may seem, it is not so easy to carry them out, because it depends upon the construction of the machine, and especially upon the mode of excitation of the field magnets, whether they can be coupled together without interfering with each other's running. For it may, and does, occur that if not rightly arranged, one machine will absorb energy from the other and be driven as a motor instead of adding anything to the energy of the circuit.

Coupling Continuous-current Machines in Series.—Series-wound dynamos may be united in series with one another for the purpose of doubling the electromotive-force. Thus two Brush machines, each working at 10 amperes, and each capable of working 6 arc-lamps, may be joined in one circuit with 12 arc-lamps in series. The only needful precaution is to see that the + terminal of one machine is joined to the — terminal of the other, precisely as with cells of the battery. Shunt-wound dynamos may also be coupled in series, though the arrangement is not good unless the two shunt coils are also put in series with one another, so as to form one long shunt across the circuit. Compound-wound dynamos may be connected in series with one another, provided the shunt parts of the two are connected as a single shunt, which may extend simply across the two armatures (double short-shunt), or may be a shunt to the external circuit (double long-shunt), or may be a mixture of long and short shunt. The same considerations apply to more than two machines. The coupling of alternate-current dynamos is considered in Chapter XXIV.

Coupling Dynamos in Parallel.—Dynamos, to run well in parallel without any special coupling devices, should have a falling characteristic (see p. 212), for if the characteristic rises, then the machine yielding the greatest share of the current will have its electromotive-force increased thereby and will yield more and more current until it takes all the load and drives the other machines as motors. If, on the other hand, the electromotive-force falls with an increase of current the load is automatically divided between the machines. It is, of course, possible for a machine to have a rising characteristic when run at a perfectly constant speed, and yet through the slowing of the engines with increased load the characteristic of the combined plant may be a falling one. In such a case, where each dynamo is driven by a separate engine parallel working would be possible.[1]

Simple shunt machines always have a falling characteristic and therefore there is no great difficulty in running them in parallel, as indeed is done on a large scale every day in central lighting stations. The chief precaution to be taken is that, whenever an additional dynamo has to be switched into circuit, its field must be turned on, and it must be run at full speed before its armature is switched into connection with the mains, otherwise the current from the mains will flow back through it and overpower the driving force.[2]

Two series dynamos cannot be coupled in parallel in a circuit without a slight rearrangement, otherwise they interfere. For, suppose one of them to fall a little in speed, so that the electromotive-force of one machine is higher than that of the other machine with which it is in parallel, the machine having the higher electromotive-force will then drive a current in the wrong direction through the other machine, reversing the polarity of its

[1] Sayers, *Journ. Inst. Elec. Engs.*, xxiv. 137, 1895.

[2] See Burstyn, in the *Zeitschrift für angewandte Elecktricitatslehre*, 1881, p. 339, also Schellen (2d edition), p. 717; Ledeboer, in *La Lumière Électrique*, xxvi. 210, 1887; Meylan, in *La Lumière Électrique*, xxvi. 379, 1887; and Feussner, in *Zeitschrift für Elektrotecknik*, 1887, 108; also Prof. Puffer in *Technology Quarterly*, v. 380, 1893. See also the special mode devised by S. S. Wheeler, U. S. Patent, No. 335,048 of 1886.

field-magnets and driving it as a motor. To obviate this, Gramme made the suggestion that the machines should be coupled in parallel at the brushes as well as at the terminals. This is shown in Fig. 519. The terminals T_1 T_1 of one machine are respectively joined to T_2 T_2 of the second machine, and a third wire joins B_1 with B_2. Triple-pole switches are convenient. If both machines are doing precisely equal work, there will be no current through the wire B_1 B_2. If either machine falls behind, part of the current from the other machine will flow through B_1 B_2 and help to maintain the excitement of the magnets of the weaker machine. This effectually prevents reversals. Another method of coupling two series machines is to cause each to excite the other's field magnetism. This equalizes the work between the two machines.

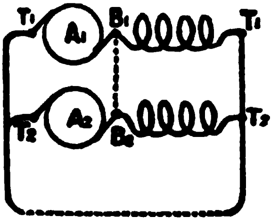

FIG. 519.—COUPLING OF TWO SERIES DYNAMOS IN PARALLEL.

Coupling of Compound Dynamos in Parallel.—In working compound dynamo machines in parallel circuit, some difficulty has been found, on account of their tendency to behave in the same manner as series-wound machines. Mr. Mordey first pointed out that the difficulty might be overcome by connecting the parallel machines in such a way that not only are the shunt portions of the field magnets in parallel circuit, but the series circuits of the field magnets are also a shunt on one another ; in other words, by connecting the brushes, as well as the terminals, in parallel circuit, precisely as Gramme has done for series-wound machines.

In Fig. 520, A_1 A_2 are the armatures of two compound dynamos, T_1 T_1 and T_2 T_2 are the terminals ; the wire B_1 B_2 acting in conjunction with the lead T_1 T_2 on the left, puts the armatures in parallel. The dynamos should each be furnished with a switch s in the shunt circuit ; they should each also have a switch m in their main circuit between the armature part and the point where the shunt circuit joins on, so that the armature part may be interrupted without interrupting the shunt circuit. The connecting wire from brush to brush, which should be at least as thick as the mains, should also be furnished with a switch z. suppose dynamo No. 1 is at work alone, its two switches s m_1, will be closed. If, now, dynamo No. 2 is to be thrown in, the following order must be observed. First get up the speed of

No. 2 to its full value, then close s_2, then z; this will fully excite its magnetism; lastly, close m_2. When No. 2 has to be thrown out of circuit the order must be exactly reversed: first open m_2; then z; then s_2; lastly, slow down the machine. A special combination-switch, which will perform these successive operations in their proper order, is desirable.

When compound dynamos are connected in this way,[1] they work quite satisfactorily, and exercise a considerable power of mutual adjustment; for any increase in the current from one machine is divided equally among the series coils and does not raise the electromotive-force of one machine more than another.

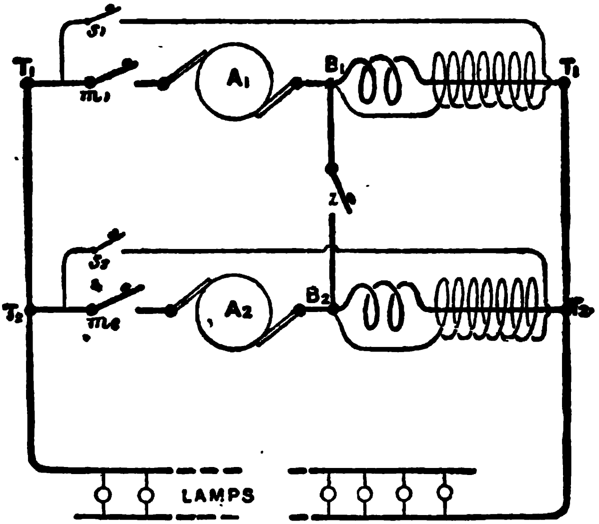

FIG. 520.—COUPLING OF TWO COMPOUND DYNAMOS IN PARALLEL.

Not only does this control exist with similar compound dynamos, but it may be relied on when the dynamos are unlike in size, power and speed. For instance, large and powerful machines may be worked in parallel circuit with smaller machines of various powers, and each will do its proper share of the work. The resistance of the series coil of each machine must, in this case, be adjusted so that the division of the current among the coils is in proportion to the powers of the machines. If the switch z is permanently kept closed the effect is to make the excitation of the field of all the machines depend upon the total output of the station, and thus it is possible to compensate for a drop in volts which takes place in the mains.

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[1] The method proposed by M. Ledeboer in *La Lumière Électrique*, xxvi. 210, 1887, is practically identical with the above.

The usual practice in English central stations, supplying continuous current is to employ simple shunt dynamos regulated by hand.

The parallel running of alternate-current dynamos is considered in Chapter XXIV.

GENERAL INSTRUCTIONS IN USE OF DYNAMOS.

Position of Dynamo.—The place chosen should be dry, free from dust and preferably where a cool current of air can be had. It should allow sufficient room for a belt of proper length, unless the dynamo is direct-driven.

Foundations.—It is most important to secure good foundations for every dynamo; and if the dynamo is direct-driven, but is not on the same bed-plate as the engine, a foundation large enough for both together should be laid down. Stone or concrete may be used, or brick built with cement, having a large thick stone bedded at the top. For small dynamos the holding-down bolts may be set with lead or sulphur in holes in the stone top; but for large dynamos the bolts should be long enough to pass right down to the bottom, where they should be secured into iron plates built in. If long holes are left in the foundations for the holding-down bolts, they should be filled in with thin cement after the latter have been put in place.

Sliding Rails.—All belt-driven dynamos ought to be provided with tightening gear to take up the slack. If the dynamo is not provided with sliding rails under its bed-plate, and tightening screws, the less desirable method of employing a tenting pulley, as in Plate IX., may be used. In any case the bed for the dynamo must be quite level, and its shaft set properly parallel with the driving pulley.

Setting up.—Before setting up any dynamo or motor which has been long unused, or has been exposed to changes of climate, it should be kept for a few days in a warm and dry place. For the insulation materials are liable to absorb damp that can only be slowly dried out. Nothing is more likely to cause a break-down than to attempt to run a machine that is not thoroughly dry.

Before Starting.—Examine the dynamo before it is set running for the first time. Remove caps of bearings and clean them and the journals. Replace them, but do not screw up too tightly. See that lubricators are filled, and the drip properly adjusted.

Where the bearings are self-oiling see that the oiling ring works properly. Use *copper* oil-cans. Turn the armature round by hand to see that nothing catches and no loose wires or waste are adhering to it. Clean up the commutator with the finest glass-paper, and note carefully that no dirt or copper-dust is lodged between the bars of the commutator. A stiff dry hog-brush will be useful here. See that the brush-holders work rightly, and the hold-off catches, if any, are in order. See that each brush is properly trimmed (i. e. filed off at the proper bevel at the ends. Some makers provide a special tool to guide the file at the proper angle). Adjust the brushes, first, by clamping them *very firmly* in their holders, so that they protrude to the proper length. For this purpose many makers provide a holder with a pointer, as at P on Plate III.) Adjust them, secondly, so that they bear with a moderate but firm pressure on the commutator. See, thirdly, that when so pressing, they bear in the right positions. For 2-pole dynamos the brushes should bear on precisely opposite bars of the commutator. For 4-pole dynamos they bear on bars that are a quarter of the circumference apart. (It is customary for makers to mark two of the commutator bars with a centre-punch so that this adjustment may be verified.) If there are two or more positive brushes abreast, try to arrange them so that the gaps between them are opposite the negative brushes so that the commutator will wear evenly. (It is well to shift the position of the brushes longitudinally from time to time.) Then, having verified these adjustments, remove all spanners and loose pieces of iron from the vicinity of the field-magnets. If there is any fear of the dynamo being started in the wrong direction, it is well that the brushes should be only lowered after starting. The current should always be turned off before the brushes are raised, otherwise a destructive spark will spoil the commutator.

It is necessary that carbon brushes should be very carefully fitted to the curvature of the commutator. One way of doing this is to paste round the commutator a strip of fine glass-paper and run the dynamo with the brushes in their normal position, until the ends are worn down to the right shape. Carbon brushes upon the whole give less trouble than copper brushes, as they do not wear the commutator so much nor do they spark so readily. A carbon brush should be free from the slightest suspicion of a crack or flaw, and a "glass-hard" corner should not be allowed to come in contact with the commutator.

The brushes being adjusted and lubricators filled, see that the connections are right, and the terminals tightly screwed down.

Bring the machine up to speed slowly, keeping a sharp look-out for anything that may be wrong, and be ready to slow down at any instant. Do not raise a brush without having turned off the current unless there are two or more brushes side by side. If the machine is shunt-wound it will at once excite itself, though the main switch is still open. If the dynamo is for supplying glow-lamps, do not on any account turn on the main switch until you see whether the machine is giving the right volts, or you may ruin all your lamps. For if the speed is too high, the volts may be too high. A pilot lamp or a voltmeter will tell you if all is right. Then, before you turn on the main switch, observe the brushes to see if there is any sparking. If there is any sign of sparks, rock the brushes forward or backward till a sparkless place is found. Not until then should the main switch be turned and the lamps lit.

Daily Attention.—It is of the utmost importance to keep a dynamo scrupulously clean. A cotton rag should be used in preference to *waste*, as the latter leaves loose ends sticking to parts where it is objectionable. An air-blast is used by the Westinghouse Co. for getting rid of dust. Besides daily lubrication, attention must be given to the brushes to see if they require to be fed forward or trimmed. The commutator should not be oiled, but only wiped with a clean oily rag or a piece of cotton cloth (*not* waste) smeared with vaseline. (This reservation does not apply to arc-light dynamos with special commutators with wide air-gaps, which may be oiled freely.) Do not let the oil creep on parts that do not require it. Oil is apt to spoil the insulating materials by rotting the varnish, and affording a lodgment for dirt and for the fine copper dust that flies from the brushes. Also, if oil gets to the commutator it will char under the brushes, forming a carbonaceous film between the commutator bars, inviting a short-circuit. This fault is less likely to occur when mica-insulation is used than when asbestos or paper is employed. It has been observed that the brushes wear and heat unequally: the positive brush wearing faster than the negative. But this is unimportant. If there is solder on the brushes, care should be taken that the soldered part should never be used for contact on the commutator; it will set up flashing sparks.

If the dynamo is driven from heavy shafting, so that there is no risk of turning backwards at starting or stopping, then the brushes may always be left down on the commutator. Many dynamos will spark at full load unless the brushes are rocked forward beyond the point that gave sparkless running on open circuit. Sparkless running is a vital matter if the commutator is to last long. The attendant cannot be too strongly impressed with the necessity of proper care on this matter. A well-designed modern dynamo, if properly attended to, will soon acquire a beautiful dark-polished surface on its commutator. But the commutator, even of a good machine, may be ruined in a few hours by careless or ignorant handling. If the brushes press too heavily it will become scored or ploughed up. If they press too lightly, or if there is vibration that causes them to jump, or if they are allowed to spark, the commutator will be worn away in patches at the edges of some of the bars, and lose its cylindricity of outline. The only remedy in this case is to carefully turn it or file it down true ; this should occur very rarely.

In central stations, and in all cases where reliability of supply is imperative, the insulation should be tested throughout the machine every day. If the insulation resistance of any part has seriously fallen (even though it may still seem sufficiently great) the machine should not be started until the cause has been ascertained and removed. A daily insulation test gives very good indication of the dryness and cleanliness of the machine.

Diseases of Dynamos.[1]

At least four-fifths of the mishaps and break-downs that occur with dynamos arise from causes more strictly within the province of the engineer than in that of the electrician. On the other hand, many of the mechanical faults that develop themselves in the machine might have been avoided had the engineer been possessed of a better knowledge of the electric and magnetic conditions which obtain in the running of the machine. It is not often nowadays that armatures fly to pieces. That disaster has seldom occurred since good engineers took in hand the construction of dynamos. The points which it is difficult for the ordinary engineer to grasp are the mechanical stresses on the copper conductors due to the magnetic field, and the necessity throughout of preserving proper insulation. All insulation being mechanically bad, he is apt, in attempting to give mechanical strength, to use the insulating materials in some way that vitiates their

[1] See paper by the author in *Electrician*, xx. 82, 1887 ; see also articles in *Electrotechnische Zeitschrift*, xi. 186, 1890 ; *Electrical World*, xiv. 99, 184, and xviii. 383, 1891 ; Crocker and Wheeler, *Practical Management of Dynamos and Motors* (Van Nostrand, New York) ; Lummis-Paterson, *Management of Dynamos* (Crosby Lockwood and Son, London) ; Parkhurst, "Diseases of Dynamos," *Trans. Amer. Inst. Elec. Eng.*, 1894.

adequacy. For want of full electrical information he may apply the insulation in an erroneous manner and produce a dynamo which will break down under the severe conditions of actual work.

Burning-out of Armatures.—Single coils of an armature sometimes get heated to redness and burn the insulation. Sometimes a whole armature will become overheated, producing a general charring. The latter case happens more often to the armatures of motors than to those of dynamos. For if any excessive current is drawn by accident from a dynamo, the torque on the armature will generally become so great as to throw off the belt or pull up the engine. Whereas, with a motor, if the armature is jammed so that it cannot turn, an enormous current will continue to flow through it if the supply be not cut off.

Short-circuits in Armatures.—A short-circuit in the armature is usually first brought to notice by the smell of burning varnish. The machine should be shut down at once, and the armature felt all over with the hand. The short-circuited windings can generally be detected by their high temperature, even if the varnish is not visibly frizzled. If the greater part of the armature is short-circuited the fault is not so easily located by the rise in temperature. If an independent source of current is available a very good plan is to pass a strong current between two opposite bars of the commutator, and compare the drop in potential between the different pairs of bars. An intelligent application of Ohm's law will generally lead to the discovery of the fault or faults. For instance, we know that if the armature is perfectly sound the fall in potential on each side of the leading-in point will be the same, so that a galvanometer whose terminals are attached to commutator bars at equal distances on each side of the leading-in point will show little or no deflection. As one passes from bar to bar the occurrence of a great deflection will immediately point to a want of symmetry at that point. The cases that might arise are so numerous that it would be useless to attempt an exposition of all of them. The experimenter must trust to his previous electrical training and the application of common sense. Where there are faults to the ironwork of the armature a current may be passed from one of the commutator bars to the ironwork, and a similar investigation made of the drop in potential between different bars. Another method is to connect all the bars of the commutator together by winding wire round it and then passing a current from this wire to the ironwork. The armature will become magnetized, the poles being in the vicinity of the faults.

A short-circuit between an imperfectly insulated wire and the iron core beneath it is a fruitful source of trouble. Not that any *one* such contact can of itself produce any effect : but that if there is one such contact, then, if a fault occurs anywhere in the lamp circuit, there will at once be developed a serious leak through earth. Also the risk of shock to persons casually touching any part of the circuit is greater if there is any single fault in the dynamo. Some firms—chiefly American[1]—prescribe that the dynamo-frame itself should be insulated from the ground. The author's experience leads him to prescribe that the framework of the dynamo should, on the contrary, be carefully connected to earth. If this is done, the risk of accident to attendants—which is considerable in the case of high-voltage machines insulated from their bed—is reduced to a minimum. A contact between an armature conductor and the iron core may occur because of the iron laminæ becoming loose and wearing through the layers of insulation. If the insulation is not waterproof and has got wet, it may break down when the machine is run. Sometimes armatures are destroyed by the burning of the insulation, by the overheating, not of the conductors, but of the iron core. In such cases the core has not been properly laminated. The burning of binding wires, which occasionally occurs, is due to want of compliance with the sufficient and necessary electrical conditions.

Being pieces of running machinery, dynamos are liable, as all engines are, to heating of bearings, if proper attention is not paid to lubrication and to the avoidance of needless dirt.

Fracture of Connections.—This most annoying fault—the fracture of the connecting pieces which lead down from the armature conductors to the bars of the commutator—appears to be partly mechanical and partly electrical. These connecting pieces pass through a partial magnetic field, and they carry at times strong currents, which are reversed twice in each revolution. Hence they are each racked by lateral forces as they rotate, and this incessantly repeated breaks them off at last. The cure is either to make them mechanically very strong, or of stranded material, or to arrange that they shall lie outside the waste field.

Disconnections in Armature.—Sometimes a disconnection occurs where the armature conductors or windings are coupled up or connected down to the commutator. The evidence of this is (i.) a sparking that cannot be stopped by rocking the brushes forward or backward, and (ii.) one or more of the bars of the commutator appearing as if burned at the edge. One way[1] of finding the location of such a fault is to run the dynamo very slowly on short-circuit. Then after a few minutes' run stop the machine and see if any of the joints of the connectors are hot; this will indicate a partial disconnection. If any entire coil is found to be hot, that is evidence not of a disconnection, but of a short-circuit. Any disconnected coil in an armature is very easily found by the fall in potential method mentioned above. If the fault cannot be remedied at once, and it is necessary to run the machine, the bar belonging to the faulty coil may be connected to the succeeding bar by a blob of solder to stop the excessive sparking and preserve the continuity of the armature.

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[1] The lightning-arresters used on many dynamos in the States are themselves a source of mishaps. If the dynamo-frame is properly earthed there is no need of a lightning-arrester on the dynamo. Efficient lightning-arresters should be fixed outside the dynamo-house where the overhead circuit enters it.

Flats in the Commutator.—Occasionally one of the commutator segments will become burned away or worn down to a lower level than the rest, or two adjacent bars may be similarly affected, causing a flat part on the cylindrical surface. Various suggestions have been offered to explain the origin of flats. If one of the bars was of unusually soft copper it might wear away faster; but the occurrence is unlikely. A partial disconnection in the armature at the part connected to the particular bar of the commutator will give rise to a spark here at every half-revolution, so biting away this bar. Flats have been noticed also to spread along the bar from a flaw at one spot.

Another undoubted cause of flats is a mechanically weak or defective means of driving. If an armature, attached by a three-legged spider, is mounted on a weak shaft that bends, it is possible that periodic vibrations may occur which will cause the brushes to jump and set up sparks at definite points around the commutator. With well-constructed armatures, well-balanced and running without vibration, there is little fear of flats if the pressure of the brushes is sufficient. Whenever a bar of the commutator shows signs of burning along its edge, steps should at once be taken to prevent the development of a flat. A fine file should be applied to smooth the surface of the commutator in the neighborhood of the threatened spot. Or, if need be, the commutator should be very slightly turned down. A narrow tool should be used for this purpose, so as not to drag the copper, and the surface should be polished with very fine glass paper and examined to see that at no spot has the thin strip of mica been bridged over by a burr at the edge of any of the bars.

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[1] Another way, applicable only to drum armatures, is due to Loomis (*Electrical Engineer*, New York, December 1891), and consists in holding the armature by hand and slowly turning it round against the torque while supplied with a current from some external source. If a position is found where it is easier to turn, it is clear that in this position the disconnection stops part of the current, so that the fault can at once be found by tracing the connectors which run from those bars of the commutator which are at the brushes in this position.

Faults in Field-magnet Coils.—Sometimes faults occur in field-magnet coils. These may be of two kinds—disconnections or short-circuits. When there is a disconnection the machine will probably refuse to excite itself. To make sure, the suspected coil should be disconnected at the ends and tested. A cell of Leclanché battery and a simple detector galvanometer, or, failing this, a common electric bell, will suffice to prove whether the wire is continuous. If the frames on which the coils are wound are loose, the resulting vibration may cause the leading-out ends of the wires to snap, perhaps at some point below the surface which can only be reached by unwinding the coil. A short-circuit between any two of the windings will have the effect of keeping the short-circuited part cool whilst the rest of the coils are hot. In a shunt coil, short-circuiting some of the windings causes the rest to overheat dangerously. A short-circuit may arise between the frames or cores and the coils, and may be also tested for by electric bell or detector as above. If there is a single contact fault of this sort between coils and ironwork in the field-magnet, then a single fault at any other point—armature, commutator, brushes, terminals or circuit—may work dire disaster.

Dynamo fails to excite.—If a dynamo fails to excite, the first thing to do is to thoroughly overhaul all the connections, particular attention being paid to the direction in which the current should circulate round the field-magnet coils: see that the brushes are in their proper position and are making good contact, and that the external circuit is open if the machine is shunt-wound, and closed if series-wound. If the dynamo still refuses to excite, lift the brushes and excite the field from some independent source, care being taken to give it the right polarity having regard to the direction of rotation and the manner in which it is connected up. In doing this it will be seen whether there is any break in field-circuit.

Faults of Alternators.—Alternators are liable to faults of special kinds. Sometimes they show a regular pulsating flicker, timed exactly to the revolutions of the armature. This can only be due to some double inequality. If one pair of poles of the field-magnet is weaker than the rest, and one of the armature coils is defective, then when these come together in position once in each revolution the current may show a momentary drop. Alternators are usually made for high voltage, and are therefore liable to faults of insulation that might not occur in low-voltage machines. If the two collecting rings are side by side on the shaft, a spark—or rather arc—may spring over from one to the other unless a high projecting washer of ebonite is interposed. The field-magnet is necessarily brought into proximity with conductors differing greatly in potential, and great care is required to prevent these being short-circuited by arcs between them and the pole-pieces. The peculiar racking action of the alternating current on the armature coils (see p. 572) is responsible for many failures in this class of machine.

Vibration and Noise.—Excessive vibration can only be due to want of proper balance in the rotating part. Vibration of a kind that may, nevertheless, be disastrous to the dynamo, racking its conductors, pounding its insulation to dust and causing the brushes to jump and spark, may be occasioned, even in a well-balanced machine, if it is not firmly secured to a proper foundation. Continuous-current machines should run practically silently; the belt will make far more noise than any part of the dynamo. Alternators do not usually run silently, for the coils of all disk armatures churn the air between the poles. If the iron cores of the armature part are subjected to too severe a cycle of magnetization they will emit a loud humming sound, which cannot be cured except by using the machine at a lower degree of excitation, being a defect of design. Once the author came across a remarkable case of an alternator which emitted a sustained howling sound of piercing loudness. The cause in this case was the accidental coincidence between the number of alternations and the natural vibration periods of some of the solid iron parts. It was cured by re-fitting the iron parts so as to alter the fulcrum from which the parts could vibrate.

APPENDIX A.

ON WIRES.

On p. 369 were given some data respecting the sizes of wire found suitable in practice for winding dynamos for different currents. Other data are to be found in the detailed descriptions of various machines in other parts of this book. The question of heating in relation to current-carrying capacity was also treated in Chapter XVI. in some detail.

A few further points may be added here, founded upon information given by wire-makers, and in particular by the London Electric Wire Company.

The usual insulation for round wires of a greater diameter than No. 16 S.W.G. is a double cotton covering which increases the diameter by amounts varying from 10 to 20 mils, but which usually averages 14 mils. For smaller sizes, from No. 18 to No. 22 S.W.G., the usual double-cotton covering is an addition of 12 mils. Square wire is usually double-cotton covered to 20 mils additional, or is sometimes braided. Laminated square wire—i. e. made of a number of narrow strips, is usually braided to about an equal amount. Since stranded wires came in for armature winding, several modes of insulating have been adopted, and one maker employs a cable of 37 wires, each No. 15 S.W.G., each single cotton covered; the whole being double-cotton covered to 16 mils additional, or braided to 20 mils. For transformer windings at high voltage a frequent practice is to wind a much thicker cotton insulation for subsequent immersion in oil. For example, a No. 23 S.W.G. wire is cotton covered to 40 mils additional, thus nearly doubling the weight of the wire.

Annexed is a table useful in magnet winding, showing the probable heating, and greatest permissible depth of winding at various amperages. It is to be remembered that 2000 amperes per sq. in. is a common density of current for field-magnets; the density in armatures runs to 3000 or more; whilst in transformers the amperage is as low as 600 or even 450 (see p. 371).

WIRE GAUGE AND AMPERAGE TABLE.

Dimensions.				Permissible Amperage, Probable Heating, and Permissible Depth.											
				1000 Amperes to sq. inch.			2000 Amperes to sq. inch.			3000 Amperes to sq. inch.			4000 Amperes to sq. inch.		
S. W. G.	Diam.	Section (sq. inch).	Turns to 1 linear inch.	A	F	D	A	F	D	A	F	D	A	F	D
22	·028	·00062	23·81	·616	0·91	4·5	1·23	3·63	1·13	1·85	8·16	·50	2·46	14·5	·28
20	·036	·0010	20·00	1·018	1·29	3·9	2·036	5·17	·97	3·05	11·6	·43	4·07	20·7	·24
19	·040	·0012	18·52	1·26	1·53	3·6	2·52	6·02	·92	3·78	13·8	·41	5·04	24·5	·23
18	·048	·0018	16·18	1·81	1·83	3·3	3·62	7·32	·83	5·43	16·4	·37	7·24	29·3	·21
17	·056	·0024	14·28	2·4	2·14	3·2	4·8	8·56	·79	7·2	19·3	·35	9·6	34·2	·19
16	·064	.0032	12·83	3·2	2·57	3·0	6·4	10·28	·74	9·6	23·1	·33	12·8	41·1	·18
15	·072	·0040	11·63	4·0	2·90	2·9	8·0	11·6	·72	12·0	26·2	·32	16·0	46·4	·17
14	·080	·0050	10·64	5·0	3·33	2·8	10·0	13·3	·70	15·0	30·0	·31	20·0	53·3	·17
13	·092	·0060	9·44	6·6	4·29	2·7	13·2	17·2	·67	19·8	38·7	·30	26·4	68·8	·16
12	·104	·0085	8·48	8·5	4·52	2·6	17·0	18·1	·65	25·5	40·7	·29	34·0	72·3	·16
11	·116	·0105	7·69	10·5	5·07	2·5	21·0	20·3	·63	31·5	45·7	·28	42·0	81·2	·16
10	·128	·0128	7·04	12·8	5·67	2·4	25·6	22·7	·61	38·4	51·0	·27	51·2	90·7	·15
9	·144	·0163	6·33	16·3	6·50	2·4	32·6	26·8	·60	48·9	58·5	·27	65·2	104·5	·15
8	·160	·0201	5·74	20·1	7.28	2·3	40·2	29·1	·59	60·3	65·5	·26	80·4	116·4	·15
7	·176	·0243	5·26	24·3	8·06	2·3	48·6	32·2	·58	72·9	72·6	·26	97·2	129·0	·15

Stranded.														
7/22	·084	·0043	9·62	4·3	2·59	4·0	8·6	10·8	·99	12·9	23·3	·44	17·2	41·4	·25
7/20	·108	·0072	7·81	7·13	3·45	3·7	14·3	13·8	·92	21·4	31·2	·43	28·5	55·2	·23
7/18	·144	·0128	6·09	12·7	4·94	3·4	25·4	19·7	·83	33·1	44·5	·39	50·8	79·0	·21
7/16	·192	·0229	5·10	22·9	7·37	3·2	45·8	29·5	·79	68·7	66·3	·35	91·6	117·9	·20
7/15	·216	·0289	4·27	28·9	7·79	3·1	57·8	31·2	·78	86·7	70·1	·34	115·6	124·6	·20
7/14	·240	·0356	3·87	35·6	8·72	2·7	71·2	34·8	·76	106·8	78·4	·34	142·4	139·5	·19
7/13	·276	·0462	3·38	46·2	9·91	2·0	92·4	39·6	·74	133·6	89·2	·33	184·8	158·5	·19
7/12	·312	·0595	3·01	59·5	11·4	1·9	179·0	45·5	·72	178·5	102·5	·32	238·0	182·2	·18

Figures in columns marked **A** signify number of amperes that the wire carries.

Figures in columns marked **F** signify number of degrees (Fahrenheit) that the coil will warm up if there is only one layer of wire; they are calculated by Esson's modification of Forbes' rule:—

Rise in temperature (Fahrenheit degrees) = 100 × number of watts lost per sq. inch.

= 69 × sectional area × number of turns to 1 inch (at 1000 amperes per sq. inch).

Figures in column marked **D** are the depth in inches to which wire may be wound if 1 watt be lost by each square inch of radiating surface, the outside radiating surface of the bobbin only being considered.

Rule for calculating a 7-strand cable:—Diameter of cable = 1·134 × diameter of equivalent round wire.

Figures under heading "Turns to 1 linear inch" are calculated for cotton-covered wires of average thicknesses of coverings used for the different gauges, viz.: 14 mils additional diameter on round wires (from No. 22), and 20 mils on stranded or square wire.

Resistance (ohms) of coil of copper wire, occupying v cubic inches of coil-space, and of which the gauge is d mils uncovered, and D mils covered, may be approximately calculated by the rule:—

$$\text{ohms} = 960700 \frac{v}{D^2 d^2}$$

The following rules which have been given by Kapp, are useful for preliminary calculations about depth of winding and weight of wire. If l is the length of wire in inches, D the depth of winding-space in inches, X the ampere-turns of excitation, P the perimeter in inches, and W the weight of the coil in pounds, we have

$$X = a\, l \sqrt{D}; \qquad [i.]$$

where a is a coefficient which depends on the gauge of wire and thickness of its insulation. Also

$$W = \beta \frac{P}{l} \sqrt{\frac{X}{1000}}; \qquad [ii.]$$

where β is a second coefficient varying with the gauge of wire.

These two formulæ are applicable to the case where a temperature-limit being imposed we allow 2¼ square inches per watt. If no such limit is imposed and a given expenditure of energy is assumed, it is more convenient to replace them by the following formulæ :—

$$X = \gamma \sqrt{W\, l D \div P}, \qquad [iii.]$$

$$W = \delta \frac{P^2 X}{1{,}000{,}000\, D}. \qquad [iv.]$$

The four numerical coefficients then have the following values :—

Diam. of Bare Wire in mils.	S. W. G.	a.	β.	γ.	δ.
40	19	522	0·495	820	0·195
120	10¼	542	0·520	850	0·205
200	5¼	570	0·615	900	0·246

Another useful rule for calculating wiring is that a copper wire 1 foot long, and 1 square mil (i. e. one-millionth of a square inch) in cross section has a resistance of 9·4 ohms, at a temperature of 60° Centig.

Yet another set of rules is convenient when calculating the size of a round wire or rectangular strip which will carry any given current with a prescribed drop of voltage.

Let C be the number of amperes the wire is to carry, v the drop of volts permitted, l the length in feet, λ the mean length per turn in feet, S the number of turns in the coil, r the resistance in ohms, W the weight in pounds, A the sectional area in square inches (if rectangular), and d the diameter in inches (if round). Obviously $r = v \div C$.

Then we have the following rules, in which the constants are chosen to suit a temperature of about 40° (Centigrade).

ROUND WIRE.	RECTANGULAR STRIP.
$d = 3{\cdot}43 \sqrt{\frac{CS\lambda}{v}} \div 10^3$	$A = 9{\cdot}2 \frac{CS\lambda}{v} \div 10^6$
$r - 11{\cdot}75 \frac{S\lambda}{d^2} \div 10^6$	$r - 9{\cdot}2 \frac{S\lambda}{A} \div 10^6$
$W - 3{\cdot}02\, d^2 S\lambda$	$W - 3{\cdot}85\, A S\lambda$

APPENDIX B.

NUMERICAL STATISTICS ON ELECTRO-METALLURGY.

The following data are useful for reference in deciding what the electrical capacity of a dynamo must be in order that it may deposit metal in any desired quantity:—

Copper.

Current	1	ampere	deposits	0·000326	grammes	per second.
"	1	"	"	0·01957	"	per minute.
"	1	"	"	1·1739	"	per hour.
"	851·8	"	"	1	kilogramme	per hour.
"	386·4	"	"	1	pound	per hour.

To deposit 100 lbs. of copper in a working day of 10 hours will require 3864 amperes of current flowing all the time; or, if conducted in ten baths in series with one another, will require 386·4 amperes, but in that case the dynamo will require to be of an electromotive-force ten times as great as for one single large bath. If electrolysis of the crude copper solution is carried on with carbon anodes, there will be required about 1·2 volts for each bath in series, or, at most, 15 volts for the ten baths.

Silver.

Current of		1	ampere	deposits	4·025	grammes	per hour.
"	"	112·7	"	"	1	pound	per hour.

Gold.

Current of 1 ampere deposits 2·441 grammes per hour.
" " 185·8 " " 1 pound per hour.

Nickel.

Current of 1 ampere deposits 1·099 grammes per hour.
" " 412·8 " " 1 pound per hour.

The following statistics as to the various pressures and currents required in various processes of electro-deposition are useful for reference:—

PRESSURE AT TERMINALS REQUIRED FOR DIFFERENT KINDS OF BATHS.

	Volts.
Copper (acid baths)	0·5 to 1·5
" (cyanide bath)	3 " 5
Silver	0·5 " 1
Gold	0·5 " 4
Brass	3 " 5
Iron (steel facing)	1 " 1·3
Nickel on iron, steel, copper, with nickel anode, strike deposit with 5 volts, diminishing to	1·5 " 2
Nickel on iron, steel, copper, with carbon anode	2 " 4
Nickel on zinc	4 " 7
Platinum	5 " 6

CURRENT DENSITY FOR PROPER DEPOSIT.

	Amperes per 100 sq. inch.
Copper Typing—	
Best quality tough deposit	1·5 to 4
Good and tough (for clichés)	4 " 10
Good solid deposit	10 " 25
Solid deposit, sandy at edges	25 " 40
Sandy and granular deposit	50 " 100
Copper (cyanide bath)	2 " 3
Zinc (for refining)	2 " 3
Silver	1 " 3
Gold	0·5 " 1
Brass	3 " 3·5
Iron (steel-facing)	0·5 " 1·5
Nickel at first deposit 9 to 10 amperes per 100 square inches, diminishing afterwards to	1 " 2

APPENDIX C.

FORMS OF SPECIFICATION.

The following hints for drawing up Specifications for tenders are intended to cover the points really necessary for securing first-class machines without too closely tying down the details.

SPECIFICATION OF CONTINUOUS-CURRENT DYNAMOS.

1. All the [four] dynamos are to be of the same [bipolar] [shunt-wound] continuous-current type with ventilated [drum] armatures. All dynamos of the same size are to have corresponing parts interchangeable. Each dynamo is to be arranged to stand upon the same bed-plate as its engine, and to be driven direct from its crankshaft.

2. [Two] of the dynamos are to be of [200] kilowatts normal output—viz. to give out normally [800] amperes at [250] volts, running at [350] revolutions per minute. The other [two] dynamos are to be of [50] kilowatts normal output—viz. to give out normally [400] amperes at [125] volts, at [450] revolutions per minute.

3. [Two] spare armatures must be supplied, one of each size.

4. The dynamos must be so constructed that when run at an absolutely constant speed, the terminal voltage, when the excitation is unchanged, shall not drop more than [5] per cent. from no-load to full load : and the shunt windings must be such that when all regulating resistance is cut out, the terminal volts at no load shall be [270] volts in the larger machines, [135] volts in the smaller machines, at normal speed.

5. The dynamos are to carry their full loads without undue heating, either from mechanical or electrical causes. The excess of temperature of any part of the armature or field-magnet above the surrounding air is not to exceed 40° Centigrade when measured on bare copper or bare iron, after a continuous run of six hours with the maximum specified output. Each armature must be so constructed that a thermometer can readily be inserted in it for ascertaining the temperature.

6. A regulating resistance is to be provided for the shunt circuit of each dynamo. This resistance is to be of either platinoid or German silver wire ; and its regulator switch must have not less than [25] contacts. Allowance must be made in the tender

for the necessary connecting wires, the switches being at a distance of [16] feet each from its dynamo, and the resistances in the place provided in the engine-room at an average distance of about [65] feet from the switches. All leads from dynamos to regulator-switches, and from regulator switches to resistances must be carried in well insulated conduits or casings. The regulating resistances are to be such that the currents they carry shall in no case exceed [1200] amperes per square inch, or that they shall not become hot enough to melt ordinary solder when carrying a current of 50 per cent. in excess of their normal maximum. They shall be enclosed in suitable fire-proof cases affording ample ventilation.

Each regulating resistance must also be such that when the dynamo is running at its full normal speed, but without load, the terminal voltage can be lowered from the normal value of [125] volts to [95] volts in the case of the smaller machines, or from [250] volts to [190] volts in the case of the larger machines ; and must also be such as to permit the terminal voltage of the smaller machines to be raised to [135] volts, and that of the larger to [270] volts.

7. The dynamos must be capable of standing a temporary overload of 50 per cent. without injurious sparking at the commutator.

8. The armature winding must be so designed with respect to the mode of connecting down to the commutator that the brushes in their normal position shall be readily accessible. The rocker must be provided with a fine adjustment, and the brush-holders must be provided with hold-off catches, as well as with devices for the regular feeding of the brushes, allowing of the utmost economy in the use of short lengths of brush. The larger machines will have [3] brushes in each range, the smaller [2].

9. The whole of the circuits are to be throughout of copper of a conductivity not less than 99 per cent. of Matthiessen's standard for pure copper ; the insulating materials used must be of the best, and be such that they will stand the application of an alternating pressure of [2000] volts between the copper and the iron parts. And when warm after a continuous run of not less than six hours, the insulation resistance between iron and copper shall not be less than [20] megohms in either the armature or the field-magnet.

10. Drawings for approval showing in sufficient detail the proposed construction of the dynamos are to be submitted with the tender. The drawings should show the mechanical construction of the armature, the mode of driving and insulation of the arma-

ture conductors, the outer bearing, and the proposed arrangements of brush-holders, terminals and lubricators. They should also show the mode of carrying the magnets upon the bed-plate of the combined plant.

11. Each dynamo when complete is to be tested, either at the contractor's works, or at the station with its own engine. The tests will include a six-hours' continuous run under maximum load; and the conditions of this specification as to output, regulation, temperature and efficiency will be rigidly enforced.

In case the same contractor supplies both dynamos and engines, the following clauses may be added:—

12. The combined efficiency of the dynamo and steam engine when under test must at least reach the following limits: The ratio of the electrical power as measured by standard amperemeter and standard voltmeter at the terminals of the dynamo, to the power developed by the engine as measured by an indicator of approved pattern shall be [86] per cent. for the [two] larger machines, and [82] per cent. for the [two] smaller machines.

13. The fact that the dynamos may have satisfactorily passed the tests, if made at the contractor's shops, shall in no way lessen the responsibility of the contractor for obtaining the like results after the machinery shall have been permanently erected in the station. The costs of these tests are to be borne by the contractor, and covered by this tender; and the tests are to be carried out to the satisfaction and in the presence of the engineer.'

SPECIFICATION OF ALTERNATORS.

1 The Alternators are to be of the [single-phase] [separately-excited] type with [stationary] armatures and [revolving multipolar] field-magnets, direct-driven. They are to be of the same size, and to have corresponding parts strictly interchangeable. Each alternator is to be designed to stand upon the same bed-plate as its engine, and to be directly coupled to its crank shaft.

2. [Four] alternators are required. They are to be of [105] kilowatts normal output, viz.: to give out normally [50] amperes at [2100] volts, running at [400] revolutions per minute.

3. The alternators are to work with a frequency of [60] periods per second; and the combined plants must be capable of running continuously in parallel at all loads.

4. The field-magnets of the alternators must be so designed that the total energy absorbed in exciting the field-magnets of any one alternator shall not exceed [2] kilowatts at full load: and they must become fully excited when supplied at [200] volts.

5. Regulating resistances must be provided, one for each alternator, in the exciting circuits. The regulating resistance of the alternators must have a sufficient range to operate if exciter circuit varies from [200] and [250] volts.

6. Special care must be taken in the design and construction of the [revolving] field-magnets that they shall be properly balanced, that under no circumstances of using shall the exciting coils shift in their places; and that all chance of either a short-circuit or a disconnection shall be made impossible. Duplicate brushes and brush-holders of substantial construction are to be furnished to each slip-ring in the exciting circuit; and the insulation of the exciting circuit in protected conduits must be very substantial.

7. The armature must be of such construction that while of great mechanical strength it admits of individual coils or groups of coils being readily replaced; whilst the armature as a whole must be accessible for daily cleaning and inspection. The terminals of the armature circuit must be specially well insulated, and protected against risk of contacts.

8. The total drop in volts, at full load, when running on an ordinary load of lamps or on a plain non-inductive resistance, must not exceed [200] volts when the excitation is kept constant.

9. The alternators are to carry their full load without undue heating either from mechanical or electrical causes. The excess of temperature above that of the surrounding air must not, in any part of the armature or field-magnet, exceed [40] deg. Centig. after a continuous run of six hours under the maximum normal load.

10. The whole of the circuits are to be throughout of copper, having a conductivity of not less than 99 per cent. of Matthiessen's standard: and the insulation shall be the best that can be procured. The insulation of the armature and of the field-magnet as between the copper conductors and the core or frame shall be such as to be capable of mechanically resisting being pierced by an electric spark, at 4000 alternating volts.

11. One spare set of armature coils or sections is to be provided by the contractor.

12. Drawings for approval showing in sufficient detail the proposed construction of the alternators are to be submitted with the tender. The drawings should show the magnetic and mechanical construction both of field-magnet and of armature; the mode proposed for securing adequate insulation of armature conductors; the proposed arrangements of the exciting circuit, slip-rings, and contact brushes, the mode of insulating the high-pressure terminals;

the bearings and proposed system of lubrication; the coupling of the shafts.

13. Each alternator when completed is to be tested, either at the contractor's works, or at the station, with its own engine. The tests will include a six-hours' continuous run under maximum load, and the conditions of this specification as to output, regulation, insulation, temperature, parallel working and efficiency will be rigidly enforced.

In case the same contractor supplies the engines as well as the alternators, the following clauses may be added :—

14. The combined efficiency of the alternator and engine when under test must at least reach the following limits : the ratio of the electrical power as measured by standard wattmeter at the terminals of the alternator, when working on a non-inductive load, to the power developed by the engine as measured by an indicator of approved pattern, shall be [82] per cent. at full load, and shall be [75] per cent. at one-quarter load. The certificate of [the Board of Trade] shall be deemed a sufficient guarantee of the correctness of the readings of the wattmeter.

15. The fact that the alternators may have satisfactorily passed the tests, if made at the contractor's shops, shall in no way lessen the responsibility of the contractor for obtaining the like results after the machinery shall have been permanently erected in the station. The costs of these tests are to be borne by the contractor, and covered by this tender ; and the tests are to be carried out to the satisfaction and in the presence of the engineer.

SPECIFICATION OF TRANSFORMER.

1. The number of transformers required is [six]. They are all to be of the [double-limb upright] type, having each an output of [20] kilowatts. The ratio of transformation is from [2100] to [105] volts ; and the normal current in the secondary circuit is [190] amperes ; but each transformer must be capable of working at a temporary maximum load of [220] amperes without injury, for a time not exceeding twenty minutes. The transformers to be wound for a frequency of [60] periods per second.

2. The cores are to be constructed of the best Swedish charcoal iron plates not exceeding [20 mils] in thickness, carefully annealed, and coated with tough insulating varnish. The core-plates when built up are to be interleaved at the joints so as to form a com-

plete magnetic circuit of uniform section, and held tightly together by insulated bolts. The assembled cores to be covered with tape, varnished with shellac varnish, and well-baked before the coils are placed upon them.

3. The primary and secondary coils are to be of copper, having a conductivity of not less than 99 per cent. of Matthiessen's standard, and are to be double-cotton covered to a depth of [20 mils] and wound on separate concentric cylinders of ozokerited compressed paper. A thin layer of insulating material to be placed during winding between every layer of wire, and in addition a sheet of ebonite at least [40 mils] thick to be interposed between the primary and secondary coils. The winding of the two secondary coils to be such that both of the ends that are to go to the two secondary terminals shall be the ends of outside layers. The whole of the insulation and materials used must be of the best quality.

4. The resistances and current densities in the copper, and the flux-density in the iron, must be such that the transformer shall be capable of working for any length of time at full normal load without overheating in any part, and on a run of six consecutive hours at full normal load shall not rise more than [50] deg. Centig. above the temperature of the surrounding air. Nor must the drop in the voltage at the terminals of the secondary coil, from no load to full load, when the primary pressure is maintained constant at the primary terminals, exceed [1½] volts when working on a non-inductive load.

5. The coil ends are to be brought to well-insulated terminal plates, inside the case and suitable terminal screws are to be provided for attachment of high and low-voltage conductors. The case is to be of cast iron, closed by a suitable cast-iron cover rendered air-tight and water-tight by a rubber packing. Metal glands bushed with ebonite are to be provided for both the low and the high-pressure conductors.

6. Drawings for approval showing in sufficient detail the general construction of the transformers, and in particular the modes of securing the transformer in its case and of leading out the conductors, are to be submitted with the tender.

7. Each transformer must have an insulation resistance between the primary and secondary windings of not less than 25 megohms; and before being tested at the works must be subjected between primary and secondary and between coils and core to an alternating pressure of at least 4500 volts. After delivery at the station each transformer is to be tested, the tests to include a six hours'

continuous run at full normal load ; and the conditions of this specification as to output, ratio of transformation, regulation, temperature and efficiency will be rigidly enforced.

8. The efficiency of each transformer when under test, and when warm after a continuous run of six hours, must at least reach the following limits: the ratio of the electrical output of power as measured by certified wattmeter at the secondary terminals, when working on a non-inductive load, to the input of power as measured by certified wattmeter at the primary terminals, at normal pressure and frequency, shall be [97] per cent. at full load and [93] per cent. at one-quarter load. The certificate of [the Board of Trade] shall be deemed a sufficient guarantee of the correctness of the wattmeter used in these tests.

9. The fact that the transformers may have satisfactorily passed these tests before delivery shall in no way lessen the responsibility of the contractor for obtaining the like results after the transformers shall have been delivered at the station. The costs of these tests are to be borne by the contractor, and covered by this tender ; and the tests are to be carried out to the satisfaction and in the presence of the engineer.

INDEX.

A

PAGE

- **Accumulator** charging, dynamos for.... 472
- *Achard*, on motor efficiency.... 492
- Activity of motor.... 492
- *Adams*, *W. G.*, on dynamo tests.... 768
- Addition of alternating quantities.... 556
- Adjustment of brushes.... 770
- Admiralty specification as to temperature rise.... 875
- Advantages of drum winding.... 803
  - Of high voltage....694, 732
  - Of open coil armatures.... 464
- Air-blast for cleaning.... 771
  - For spark prevention.... 463
- Air friction.... 106
- Air-gap in magnetic circuit.... 128
  - Effect of increase of.... 884
  - Effect of widening.... 879
- *Alioth & Co.'s* alternators.... 686
- *Allgemeine Elektricitäts Gesellschaft*—Alternators.... 627
  - Continuous-alternating transformer.... 781
  - Inductor alternators.... 642
  - Motors.... 538
  - Regulator.... 745
- "Alliance" machine.... 10
- *Alteneck*, *von Hefner*—Disk dynamo.... 479
  - Drum-wound armature.... 15
  - Graphic construction of transmission.... 788
- Alternate current—Principles of....547, 551
  - Analytical theory.... 573
  - Electro-magnets.... 566
  - Polyphase....555, 579, 628, 662
  - Of extra high frequency.... 570
  - Skin effect.... 578
  - Transformers.... 695
  - Transmission of energy by.... 786

PAGE

- Alternate-current motors—Monophase 687
  - Polyphase 662
  - Retarded field 698
  - Series 693
  - Split-phase 689
  - Synchronous 647
- Alternating-continuous transformers 728
- Alternating and rotating vectors 690
- Alternators 579
  - As motors 647
  - Armature winding of 580, 597
  - Asynchronous 606
  - Construction of 601
  - Coupling of 647
  - Excitation of 594
  - Faults of 776
  - For constant current 595, 640
  - For constant voltage 595
  - Fundamental formula of 46, 658
  - In parallel 659
  - Specification of 787
  - Torque of 571
  - Width of pole-faces, &c 588
- Aluminium, dynamos for reducing 412, 471
- Amperage 340, 346, 371, 622, 779, 780
- *Ampère*, on early dynamo 7
- *Ampère's* rule as to direction of electromotive-force 22
- Ampere-turns 117
  - Required on magnetic circuit 148
  - Calculation of 350, 356, 361, 364
- Amperes, virtual 554
- Amplitude of alternating quantity 550
  - Of magnetic cycle 136
- Analogy between electric and magnetic circuit 119
- *André's* motor 522
- Angle of lag of current 556, 562
  - Of lead of current 566
  - Of lead of brushes 72, 85, 382, 448, 395, 514
  - Of polar span 74, 387, 588
- Angular speed 101, 173, 367, 549, 675
- Anti-friction bearings 333
- Apparent resistance of armature 89
- Apparent watts 567
- *Appold's* improvement of Prony brake 754
- *Arago's* rotations 66
- Arc lighting—Alternators 595, 640

PAGE
Arc-lighting Dynamos.. 445
Armature, winding of..............................301, 447
Characteristic of.. 205
Armature—Balancing of........................295, 331, 775
Binding of...................................43, 106, 296
Bar...296, 304
Burning out of.. 773
Closed coil.. 39
Construction of...................................284, 580
Coils of.. 243
Coils wound on formers............................301, 310
Coils of alternator, breadth of.. 588
Connecting up of....................581, 585, 587, 590, 596
Core of..............41, 45, 90, 284, 286, 290, 367, 451, 583, 602
Compensation...................................388, 391, 394
Cooling surface of.. 375
Definition of..3, 34
Diameter of.......................................342, 377
Disk..............................43, 278, 442, 585
Design of.......................................341, 602
Drum....................15, 41, 76, 244, 255, 265, 302, 583
Exploration of.. 63
Faults of.. 773
Gyrostatic action of.. 328
Heating of...........................295, 369, 375, 773
Insulation of...................44, 294, 296, 452, 616, 623
Iron in...593, 602
Length of...........................342, 377, 386, 398
Open coil..40, 447
Pole..43, 584
Practical construction of.. 284
Reaction of.................70, 380, 387, 478, 510, 596, 654
Ring...........................40, 245, 258, 275, 300, 580
Support of.. 327
Torque of.......................................96, 100, 102
Ventilation of..................164, 292, 295, 403, 616, 622
Winding of................243, 289, 297, 342, 369, 452, 580
Arnold, on alternate-current motors.. 21
On armature winding.. 21
On homopolar induction.. 478
On multipolar rings.. 278
Arnoux, on disk winding.. 280
On widening of gap-space.. 380
Asynchronous generators.. 606
Asynchronous motors.. 662

PAGE

Atkinson Ll. B. (*see* also Goolden)
  Homopolar dynamo.................................. 477
  Mining motor.................................. 539
  Pulsating motor.................................. 546
Auerbach, on theory of dynamo.................................. 20
Augmentor.................................. 718
Automatic regulators (*see* Regulators)
Auto-transformers.................................. 718
Auxiliary winding on armatures.................................. 394
Average electromotive-force..................................172, 555
Ayrton, W. E., on armature reaction.................................. 86
  On size and output.................................. 110
  On dynamo testing.................................. 763
  On power transmission.................................. 492
Ayrton & Perry, on brake dynamometer.................................. 755
  Constant-speed motors..................................18, 521, 522
  Motor.................................. 532
  On magnetic shunts.................................. 155
  On sparkless commutation.................................. 515
  On spurious resistance.................................. 89
  On thickness of gap-space.................................. 398
  On transmission of power.................................. 740
  Periodic governor.................................. 521

B

BACK electromotive-force (*see* Counter electromotive-force.)
Backward lead of brushes..................................87, 395, 396, 514
Baker, on self-excitation.................................. 12
Baking and drying armatures.................................. 300
  Commutators.................................. 317
Balance method of measuring power.................................. 756
Balancing of armatures..................................295, 331, 775
Ball bearings.................................. 333
Bar armatures..................................298, 304, 402, 405, 480
Barlow's rotating wheel.................................. 17
Barr, Beeton and Taylor, on wave form.................................. 553
Barr, Burnie and Rodgers, on wave form.................................. 553
Bars of commutator (*see* Commutator)
Bast, De, on rotatory-field motors.................................. 21
Baumgardt, on compound winding.................................. 242
Bearings.................................. 332
  Pressure on.................................. 327
  Self-oiling.................................. 336
Bedell and Crehore, on graphic constructions for alternating currents.................................. 552

PAGE
Bedell, on mutual induction........ 720
Bedell, Miller and Wagner, on finding form of wave........ 553
Bedell and Ryan, on synchronous motors........ 21, 651, 654
Bed-plates........ 152, 159, 337, 769
Bell, Louis, on compound winding........ 242
Belt-collectors........ 326
Bending stress on shaft........ 331, 775
Berlin central station dynamos........ 407
Berlin type of ring armatures........ 275, 302
Bifurcation of current........ 257
Binding-wires........ 43, 296
Blakesley, T. H., on alternating currents........ 552
    On three-dynamometer method........ 568
Blakey-Emmott alternator curve........ 553
Blondel, on synchronism of alternators........ 21, 653
Bollman disk dynamo........ 479
Booster........ 726
Borel's motor........ 689
Bosanquet, on magnetomotive force........ 116
Bourbouze's motor........ 483
Brackett's method of measuring power........ 757
Bradley, C. S.—Arc-light dynamos........ 465
    On polyphase work........ 665
    Two-phase alternator........ 599
    Two-phase motor........ 671
Brake for measuring power........ 754
Branched magnetic circuits........ 119, 150, 165
Breadth of brushes........ 313, 320
Breadth-coefficient........ 589, 592
Breguet, A., on theory of dynamo........ 4
Brett's self-exciting dynamo........ 9
Brotherhood's coupling........ 338
Brousson, on alternator's output........ 589
Brown, C. E. L.—Alternators........ 632
    Arrangement of alternator coils........ 604
    Cylindrical winding........ 310
    Dynamos........ 415
    Electro-metallurgical dynamos........ 413, 472
    Four-pole dynamos........ 409
    Flexible-band collector........ 326
    Homopolar dynamo........ 477
    Method of driving core-disks........ 292
    Motors........ 410
    Multipolar field........ 165, 397, 409
    Pierced core-disks........ 99, 290, 628
    Polyphase motors........ 673

PAGE

Brown, *C. E. L.*—
    Three-phase alternator.. 627
    Three-phase inductor alternator.. 646
    Transformer.. 705
Brown, Boveri & Co. (*see* Brown, C. E. L.)
Brush—Arc-lighting dynamo.. 451
    Commutator.. 454
    Machine characteristic.. 205
    Open-coil dynamo.. 16
    Uses shunt and series coils.. 56
    Electro-plating dynamo.. 470
    Induction sheath.. 451
    Regulator.. 746
Brush Electrical Engineering Co.—Alternators.. 619
    Dynamos.. 417
Brush-holders.. 321
    Insulation of.. 324
Brushes..32, 312, 318
    Carbon..319, 770
    Care of.. 770
    Lead of..72, 76, 78, 85, 382, 395, 448, 514
    Of arc-light dynamo..448, 454
    Thickness of.. 320
    Position of..514, 786
Burgin machine.. 285
Burning out of dynamos.. 773
Burstyn, on parallel running.. 766
Bushed pole.. 393

C

Cabanellas, on continuous-current transformation.. 727
    On spurious resistance.. 90
    On demagnetizing effect of eddy-currents.. 92
Calculations of dynamo..339, 345
    Of efficiency.. 347
    Of magnetic circuit..348, 350, 356, 361, 364
Caldwell's regulator.. 747
Capacity in circuit..564, 576
    In mains.. 566
Carbon brushes..319, 320, 770
Cardew, Major, on dynamo testing.. 758
    Voltmeter.. 554
Carhart, on Jacobi's law.. 500
Carpentier, on brake dynamometer.. 755
Cast iron, magnetic properties of.. 122

PAGE

Causes of sparking..79,83, 331
Centrifugal governors.. 520
C.G.S. magnetic units.. 144
Characteristic curves.. 196
    Of separately excited dynamo.......................... 185
    Drooping..466, 766
    External.. 202
    Internal.. 210
    Relation of, to winding.......................... 207
    Of motors..502, 505
Choking coils.. 566
Coking coil, transformer as.. 698
Circuital distribution of vectors.. 115
Circuit—Electric.. 26
    Magnetic.. 114
Circulation of power.. 758
Circumflux..383, 384
City and South London Railway plant.. 545
Clarke's dynamo..8, 479
Clausius, R., theory of dynamo..20, 190
Cleaning dynamo.. 771
Clerk Maxwell (*see* Maxwell)
Clock diagram..550, 591, 648, 652
Closed-coil armature..37, 39, 61
    Magnetization of.. 71
    Two paths through..60, 62
    In arc-light dynamos.. 466
Coefficient of leakage.. 151
    Of self-induction..560, 720
    Of transformation..697, 720, 727
Coercive force.. 133
Coils—Of alternator.. 604
    On transformers.. 704
    Position of magnetizing.. 150
Collars on shaft.. 331
Collecting rings..312, 326, 335
Collector (*see* Commutator)
Combined plant.. 762
Commercial efficiency.. 347
Commutation—Diameter of.. 78
    In motors.. 514
Commutator..32, 37, 40, 312
    Bars..30, 313
    Care of..770, 771
    Distribution of potential on..66, 68
    Exploration of.. 68

PAGE

- Commutator—
  - Flats in, 775
  - For rectifying, 594
  - Invented by Sturgeon, 9
  - Of Berlin dynamos, 302, 407
  - Of Brush dynamo, 452
  - Of open-coil dynamos, 447
  - Of Thomson-Houston machine, 450
  - Of tramway generator, 434
  - Outer portions of conductors as, 275, 302, 407
  - Sparking at (*and see* Sparking), 78
- Commuting coils, 438
- Comparison of single and polyphase alternators, 601
- Compensated armatures, 386, 388, 391, 394
- Compound dynamos, coupling of, 767
- Compound winding, 17, 55, 233, 522
  - Calculation of, 363
  - Experimental determination of, 366
  - In arc-light dynamos, 446
  - In motor, 522
  - In alternators, 595
  - Slow in action, 142
- Compression, effect of, on magnetization, 294
- Concentration of field, 398
- Condenser, action of synchronous motor, 654
- Conductors—Drag on, 96, 103
  - Embedding of, 99
  - Kinds of, on armatures, 299, 343
  - Lamination of, 343
  - Moved in magnetic field, 22
  - Number of, 168
- Connecting up alternate-current armatures, 581, 585, 587, 590, 596
- Connectors, 304
  - Junction with commutator, 318
- Consequent poles, 161
- Constant-current, 502, 508, 512
  - Alternators for, 595, 640
  - Dynamos for, 445
  - Motors for, 530
  - Regulators for, 744
  - Transformers for, 717
- Constant electromotive-force, 182
- Constant speed, 502, 511, 522, 529
- Constant torque, 502, 508, 749
- Constant voltage, 54, 505, 508, 511, 523
  - Dynamos, 54, 224

PAGE
Constant voltage—
    Alternators.................................... 595
    Regulators...................................... 744
Construction, practical, of armatures.................. 342
    Of alternators.................................. 601
    Of commutators.................................. 315
    Of motors.................................. 531, 673
    Of transformers................................. 700
Continuous-alternating transformers.................... 728
Continuity of current..................................33, 176
Continuous and alternate-current windings.............. 587
Continuous-current dynamos............................. 399
    Calculation of.................................. 353
    Coupled in series............................... 765
Continuous-current motors...........................482, 531
Convertible alternators................................ 636
Converters (*see* Transformers)
Cooke uses electromagnet in dynamo................... 9
Cooling surface of magnet coils..............373, 397, 622, 717
Copper—Amount expended on line......................... 740
    Deposition of................................... 783
    Heat waste per lb............................... 371
    Specification of conductivity.............786, 788, 790
    Specific utilization of.....................368, 626
Copper and iron losses in transformers.......700, 703, 715, 717
Cores of armature...............41, 43, 44, 284, 451, 583, 602
    Of rotor and stator............................. 674
    Of transformers................................. 702
Core-disks...284, 367
    Methods of driving.............................. 291
    Toothed.........................286, 433, 544, 583
    Pierced..............................290, 625, 674
Counter electromotive-force in motors...............485, 496
    In synchronous motors.......................649, 651
    In transformers.............................697, 709
Couple (*see* Torque)
Coupling of alternators................................ 647
    Of dynamos...................................... 765
Couplings for direct driving........................... 337
Cotton covering of wires............................... 779
Creeping, magnetic..................................... 141
Critical current....................................... 209
Critical speed...........................210, 478, 525, 752
Crocker, F. B., on high voltage dynamos...........466, 473
Crocker-Wheeler—Core-disks........................... 287
    Motors.....................................533, 536

PAGE

Crocker-Wheeler—
  Motor-generators........ 725
  Self-oiling bearings........ 336
Crompton, R. E., on efficiency of dynamos........ 762
  On end-connecting........ 307
  On compound winding........ 57
  On ring windings........ 301
  On stranding conductors........ 299
Crompton & Co.'s dynamos........17, 401, 471
Cross-compounding........ 389
Cross-connecting ring armatures........ 276
Cross magnetization........70, 382, 679, 681
  In motor........ 514
Current and torque........ 102
Current, alternating........547, 551
Current-carrying capacity of wires........ 779
Current-density, effect on heat waste........ 370
  Permissible........340, 346, 370, 622, 779
Current in conductors, method of indicating direction of........ 73
Curve of integrated electromotive-forces........62, 66, 68, 78
Curves of magnetization........ 122
Cutting of magnetic lines........22, 27, 168, 475, 549, 675, 696
Cycle of alternating current........ 551
  Of magnetization........ 133
Cylindrical winding, Brown's........ 310

D

Dal Negro, his machine........ 7
  Motor........18, 483
Damp, effect of........ 769
Data of machines of various sizes........ 430
Data (*see* Tables)
Davenport's motor........ 18
Davidson's motor........ 18
Dead turns........88, 92, 206
De Bast, on rotatory-field motors........ 21
Definition of dynamo machine........ 1
De la Rive, on magnetic circuit........ 115
Demagnetizing effect of armature........70, 84, 353, 364, 380, 387
  In motor........514, 530
  In alternator........595, 654
  In rotor........ 681
  In transformer........ 698
  Of eddy-currents........84, 515
Density of current........340, 346, 370, 622, 779
  Of magnetic flux........115, 119, 342, 368, 430, 605, 715, 716

PAGE
Deposition of metals....468, 783
Deprez, Marcel, on characteristic curves....198, 200, 204
  On compound dynamos....55, 239, 446
  On constant potential dynamos.... 17
  Design for dynamo.... 400
  On field-magnets.... 161
  On law of similars.... 109
  Method of measuring power.... 757
  On regulating motors.... 520
  On theory of dynamo.... 20
  On transmission of power.... 18
  On two-phase combinations.... 663
Depth of winding.... 780
Deptford station plant.... 618
Derivation (*see* Shunt)
Design of dynamos....45, 339, 396
  Of alternators.... 588
  Of motors.... 531
  Of transformers.... 715
Desroziers—Disk dynamo....43, 442, 480
  Disk-winding....280, 282
  Magnetic shunt.... 744
Developed winding diagrams....249, 597, 630
Diacritical current.... 144
Diameter of commutation....33, 78, 448
  Of shunt wire.... 372
Difference of phase....556, 560, 571, 598, 649, 663, 709
Differentially-wound motor.... 522
Direction of electromotive-force.... 22
  Of magnetic lines.... 113
Discoidal ring armatures....41, 284, 296, 417
Diseases of dynamos....83, 464, 772
Disk armatures....41, 43
  Winding of.... 278
  Of alternators....585, 614
Disk Dynamo, Edison's....16, 279
  Faraday's.... 5
  Pacinotti's....15, 279, 479
  Fritsche's....44, 279, 479
  Desroziers's....43, 280, 442, 480
Disks for armature cores....284, 288
Distortion of magnetic field....69, 72, 74
  Prevention of....388, 393
Distribution of potential on commutator....66, 68
Distributive winding....588, 626
Dobrowolsky, von Dolivo—Alternators.... 627

PAGE

Dobrowolsky, von Dolivo—
  On bushed poles....393
  On polyphase work....665
Double magnetic circuit....150, 160, 167
Douglas and Laxey railway plant....426
Douglass on early dynamo....10
Dove on magnetic circuit....115
Drag in case of embedded conductors....99
  On armature by distorted field....75, 76
  On conductors....96, 103, 486
Drawings, specification as to....786, 788, 790
Dredge, on theory of dynamo....4
Drehstrom....665
Driving horns....106, 296
Driving spokes....290
Drum armature....15, 41, 303
  Design of....339
  For alternators....583
  Reaction of....76
  Winding of....244, 255, 265, 302
Drying armature....300
Dub, on magnetic circuit....115
Du Bois, on magnetic properties of iron....127
Dujardin's "inductor" machine....10
  Oscillatory dynamo....16
Du Moncel, Count, his early work....4, 10
Duncan and *Hassen*, on dynamo tests....764
Duncan, L., on alternate-current motors....21
Dynamo—As motor....18
  Definition of....1
  Parts of....2
  Diseases of....83, 464, 772
  Early forms of....5 *et seq.*
  Management of....765, 769
  Origin of word....13
Dynamometer....755
Dynamometric governors....521, 749

E

Economic coefficient....107, 185
Economy of transmission....735, 740, 742
Eddy-currents....90, 93, 299
  Demagnetization due to....84, 515
  Driving of motors by....665
  Loss, calculation of....187

PAGE
Eddy-currents in transformer....689, 760
Edison, T. A., on auxiliary winding.... 394
    On continuous-current transformation.... 727
    Disk dynamo....16, 279
    Early dynamo.... 16
    Regulator.... 226
    Standard dynamo.... 427
    Method of end-connecting.... 805
Edison Co.'s dynamos.... 427
Edison-Hopkinson dynamo.... 421
    Calculations of.... 353
    Efficiency of.... 195
Effective volts and amperes.... 554
Efficiency calculations.... 347
Efficiency—Commercial.... 186
    Electrical....185, 186
    Of combined plant.... 762
    Of dynamos....107, 185, 759
    Of motors....487, 490, 497, 676
    Of transformers, effect of wave form.... 712
    Of transmission of energy....735, 740, 742
    Testing.... 753
    Specification of....787, 789, 791
Eickemeyer's armature winding.... 810
    Dynamo.... 164
Electrical efficiency.... 347
Electric governing of motors.... 521
Electric motive power, theory of.... 489
Electric railway plant....424, 426, 540
Electro-metallurgy statistics.... 783
Electro-metallurgical dynamos....418, 468
Electromotive-force in moving conductor....22, 29
    Addition of, in closed-coil armatures.... 61
    Alternating.... 548
    Average....174, 554
    Of dynamos, factors of.... 45, 168
    Fluctuation of.... 175
    Of alternators....589, 590
    In transformers.... 696
Electro-plating dynamos....8, 418, 468
Elliptically-rotating field.... 664
Elmore's electro-plating dynamos.... 469
Elphinstone, Lord, his multipolar drum.... 16
Elwell-Parker—Alternator.... 584
    Electro-plating dynamo.... 470
    Motor generators.... 725

PAGE
Embedding conductors in iron.. 99
Emission of heat at surface.. 373
End connectors.. 304
End play of shaft..331, 338
    Prevention of.. 333
End plates of armature core.. 293
Energy, where expended, where utilized..96, 487
Equations of dynamo..46, 170
    Of motor.. 494
    Of alternator..46, 549
    Of alternator as motor.. 658
    Of asynchronous motor.. 684
    Of transformer..696, 699, 722
    Of motor generator.. 728
Esson, W. B., on armature reaction..72, 382, 384
    On arc-lighting dynamos.. 465
    On binding wires.. 297
    On load curves.. 381
    On multipolar machines..21, 396
    On permissible heating.. 373
    On peripheral speed..367, 375
    On size and output.. 110
Ettingshausen's machine.. 8
Evershed, on transformer design.. 716
Evolute connectors.. 305
Ewing, on magnetic properties of iron..127, 129, 135
    Magnetic tester.. 137
    Method of exploring commutator.. 66
Excitation of field-magnets..47, 52, 56, 197, 210, 224, 594
    Of synchronous motors.. 652
Excite, dynamo fails to.. 776
Exciting current in shunt.. 370
Exploring electromotive-force of armature..63, 73
External characteristics..202, 210
Extra-high-pressure dynamos.. 473

F

FAILURE to excite.. 776
"Falcon" dynamos.. 419
Faults in armature.. 772
    In field-magnet coils.. 776
    Of alternators.. 776

PAGE

Faraday, Michael—Discovers induction 1, 3, 22
  His disk dynamo 5
  Electromagnetic rotations 17
  His researches 5, 6, 7
  On magnetic circuit 115
  On magnetic lines 26
  His ring 695
Farmer, Moses G., on self-excitation 12
Favre's researches 19
Feathers 337
Fein's dynamos 406
Feldmann, on alternating-current wave form 713
Ferranti's alternators 16, 585, 586, 613
  Mains, capacity effect 566
  Rectifiers 731
  Transformers 707, 714
Ferraris, Galileo, on magnetic rotation 21, 664, 665
  On monophase motors 690
Feussner, on parallel running 766
Field—Concentration of 393
  Magnetic 113
Field-magnets 34
  Advantage of powerful 95, 380
  Branched 119, 153, 159, 473, 601, 629
  Design of 341, 344, 378
  Excitation of 47, 52, 56, 197, 210, 224, 594
  Forms of 158, 378
  Formulæ for 143
  Of motor 515
Finzi, on hysteresis 141
Fischer-Hinnen, on armature compensation 391
"Flashing over" 83, 464
Flats on commutator 775
Fleming, J. A., on alternating currents 552
  On alternate-current wave form 712
  On capacity effect in mains 566
  On finding form of wave 553
  On measurement of alternate-current power 568
  On loss in transformer iron 137
  On reluctivity 144
  Rheostats 744
  Rules as to force on conductors 22, 96
  On transformers 552, 712, 718
Fluctuations of electromotive-force 178, 464
Flux-density 115, 119, 120, 342, 368, 430
  In alternators 605

PAGE

Flux-density—
  Calculation of.................................348, 360, 364
  Effect on losses in armature.................................. 763
  In multipolar machines.................................. 397
  In transformers.................................138, 715, 717
Flux—Magnetic.................................114, 145
  Regulation of.................................. 744
Fontaine's transmission of energy.................................. 734
Fontaine and Gramme, transmission of power.................................. 18
Fonvielle, on rotation of iron disk.................................. 687
Forbes, Prof. George, on carbon brushes.................................. 319
  Designs for Niagara plant.................................. 636
  On homopolar dynamo.................................. 476
  On transmission of energy.................................. 741
Force on conductor in magnetic field.................................. 8
Form of wave of alternating currents.................................549, 711, 713
Formulæ for the electromagnet.................................. 143
Foucault currents.................................. 90
Foundations.................................. 769
Foundation ring for armature.................................284, 291, 417
Fourier's series.................................. 569
Frankfort—Central station plant.................................. 634
  Exhibition tests.................................. 764
  Transmission.................................. 741
Frequency.................................549, 560, 574
  High.................................570, 578
  Usual.................................. 579
Friction.................................106, 332
  Measurement of loss by.................................. 761
Fringe of field.................................81, 155, 355, 361, 393
Frith, on flux regulation.................................. 744
Fritsche, on armature winding.................................21, 244, 272
  On disk winding.................................280, 480
Frölich, Dr. O., on armature reaction.................................. 86
  On characteristic curves.................................. 200
  On compound motors.................................. 528
  On electromagnet.................................. 143
  Equations of electromagnet.................................. 20
  On eddy-currents.................................. 90
  On Siemens' dynamos.................................. 405
  On size and output.................................. 109
Froment's motor.................................18, 484
Froude's brake dynamometer.................................. 755
Full load, calculations at.................................. 363

G

PAGE

Gaisberg on armature distortion.... 69
Ganz's dynamos.... 406
Ganz-Zipernowski alternators.... 611
Gap in magnetic circuit—Effects of.... 128
    Thickness of....387, 398
    Widening of.... 379
Gaugain, J. M., on curves of integrated electromotive-forces.....4, 62
Gauge of wire for armature....342, 346, 369, 779
Gauss, the....119, 144
Gauze for brushes.... 318
General Electric Co.'s Alternators.... 626
    Dynamo.... 482
    Railway motors.... 546
Genoa transmission of power.... 786
German-silver, use of....622, 785
Gilbert, the.... 144
Goerges on output of polyphase machines.... 601
Gold, deposition of.... 784
Goolden & Co.'s Brush-holder.... 825
    Dynamos.... 484
    Mining motor.... 539
    Regulator.... 745
Goolden-Willans plant, test of.... 764
Gordon's alternators....16, 599, 607
Governing—By steam-pressure.... 749
    Dynamometric.... 749
Government of motors.... 519
Governors....226, 468, 625, 743, 748
Gramme—Alternator....580, 582
    Armature....15, 41
    Dynamos.... 400
        " characteristic of.... 206
    Motor generator.... 724
    On coupling of series dynamos.... 767
    Transmission of power.... 18
Graphic treatment in alternate-current work.... 561
    Of asynchronous motors.... 682
    Of continuous-current motors.... 496
    Of dynamos....66, 196, 239
    Of monophase motors.... 692
    Of transmission.... 788
    Of synchronous motors.... 652
Gülcher Co.'s brush-holder.... 822
    Commutator.... 315
Gyrostatic action of armature.... 828

H

PAGE

Hagenbach on theory of dynamo........ 20
Heat, effect of, on magnetization........ 181
Heat, waste in polyphase motors........ 677, 678
Heating and surface emission........ 373, 717
  Of armatures........ 295, 372, 773
  Of cores........ 90, 137, 715
  Of magnet coils........ 369
  Of pole-pieces........ 70
  Of wires........ 782
  Specification of maximum........ 752, 785, 788, 790
"Hedgehog" transformer........ 707, 714, 717
Hefner Alteneck (*see* Alteneck).
Helios Co.'s alternator........ 611
Helmer, design of........ 478
Heilmann locomotive dynamo........ 415
Heinrich's dynamometer........ 756
Heisler's constant-current alternators........ 640
Henley's inductor dynamo........ 10
Henry's motors........ 17, 488
Henry, the........ 560
Hering, *Carl*, on armature winding........ 21, 244
  On homopolar induction........ 478
  On magnetic leakage........ 152
Herrick, on rheostats........ 744
Herwig, on theory of dynamo........ 20
Heteropolar dynamos,........ 475
Heteropolar induction........ 475
High frequency........ 570
  Skin effect........ 578
High voltage—Dynamos........ 478
  Commutators for........ 446, 465, 478
  In transmission........ 694, 782
Historical notes........ 5
Hjorth, *Sören*, his machines........ 11, 56
Hochfelden transmission........ 788
Hochhausen's designs........ 400
Holes in core-disk........ 99, 286, 290, 604, 625, 628
Holmes's dynamos........ 10
Holmes J. H. & Co.'s, dynamos........ 486
Holmes-Willans combined plant, efficiency of........ 762
Homopolar dynamos........ 475
Homopolar induction........ 5, 475
Hoppe, on homopolar induction........ 478

PAGE
Hopkinson, Drs. J. and E., on dynamo design.............20, 421, 423
  On excitation by backward lead....... 87
  On alternators............ 612
  On magnetic circuit.............................. .....145, 153
Hopkinson, Dr. J., on armature reaction......................... 382
  On coupling alternators............ ....21, 573
  On characteristic curves.......... 198
  Electro-plating dynamo....... 470
  On loss of power in magnetization.. 140
  On magnetic properties of iron............................ 122
  On magnetic calculations................................. 117
  Method of end connecting................................ 306
  Modification of Edison dynamo.......................353, 421
  On railway motors...................... 545
  On retardation of magnetism............................ 142
  On reversing gear.................................. 518
  On size and output........ 108
  On testing dynamos......................... 758
  On theory of alternate currents............................ 573
  On theory of transformers.............................. 719
  On torque of motors.................................... 509
Horns, or pole tips.... ....80, 93, 393
Horns, driving.. 296
Horse-power of dynamos and motors......................102, 531
Horse-power testing....................................... 753
Hospitalier, E................ 242
Housman, on armature compensation....................... 389
  On separation of losses......................... 761
Houston, E. J. (*and see* Thomson-Houston).................... ... 458
Hummel, on causes of losses............................ 764
Humphrey and Powell, on transformer-current curves............. 711
Hunt, R., on electromagnetism as a motive power................ 484
Hurmuzescu's dynamo.................................. 478
Hutin and Leblanc, on alternate-current motors.... 21
  Alternating-continuous transformer....................... 729
  Ammortisseur........................ 392
Hysteresis..106, 133
  Loss........ ....135, 137, 760
  Increase of, with time................ 142
  In transformer............... ....698, 712, 715, 717
Hysteretic constants.................... 137

I

PAGE

IDLE coil 67, 449
Idle current (*see* Wattless current)
Idle wire 41, 420
Imbricated conductors 402
Imbricated joints in iron 707
Immisch's motors 532
  Reversing gear for 518
Impedance 562
Impressed field 678
Indicator diagrams 753
Inductance 560
Induction coil 695
Induction of electromotive-force 1, 3, 22, 24, 29
Induction in uniform field 61
"Induction," magnetic (*and see* Flux-density) 120
Inductor alternators 10, 640
Instantaneous value of electromotive-force 549
Insulating materials—Air 315, 705
  Asbestos 44, 314, 614, 629, 771
  Canvas 294, 432, 453
  Cotton 779
  Cotton cloth 452
  Ebonite 322, 325, 326, 429, 619, 623, 707, 708
  Enamel 294, 299, 621
  Fibre, hard white 296, 314, 324, 432
  Film of oxide 285, 299
  Film of oil 299
  Glass 616
  Indiarubber 294, 533
  Insulating paint 294
  Ivory 483
  Japan 294
  "Made mica" 429
  Mica 44, 284, 294, 314, 429, 614, 623, 771
  Muslin 429
  Oil 429, 705
  Oiled linen 431
  Paper 294, 302, 451, 705
    " core-papers 429
    " Manilla 294
    " oiled 431
    " paraffined 294
    " parchmentized (Willesden paper) 294, 314, 533
    " pressed board 429
    " varnished 285, 294, 451

PAGE

Insulating materials—
  Plaster........ 314
  Porcelain........ 616
  Rope, hard........ 429
  Rubber varnish (Scott's)........ 294
  Shellac........314, 358, 451
  Silk........299, 623
  Slate........621, 623
  Sulphur........ 616
  Tape........285, 301, 425, 431, 621, 705
  Varnish........44, 285, 294, 429, 451, 705
  Vulcanized fibre........ 614
  Wood........290, 296, 314, 703
Insulation of armature cores........43, 284, 294
  Of brush-holder........ 324
  Of collecting rings........ 326
  Of commutator........ 314
  Of dynamo from ground........ 774
  In transformers........ 703
  Of wires........ 779
Insulation resistance........ 753
  Specification of........786, 788, 790
Insulation tests........ 773
Intensity of magnetic field........ 113
Interchangeability of parts........785, 787
Interference of armature (*see* Armature reaction)
Isenbeck, on armature exploration........ 63
  On curves of integrated electromotive-forces........ 62
Iron and copper losses in transformers........700, 715, 717
Iron in armature of alternator........593, 602
Iron, magnetic properties of........112, 122
Iron (*see* Armature, Cores, Flux-density, Hysteresis)

J

Jackson, Prof. D. C., on magnetic properties of iron and steel........ 127
Jacobi, on back electromotive-force of motors........ 485
  On early dynamo........ 8
  On electromagnet........ 143
  On law of maximum output........491, 494, 498
  Law of, applicable to alternators........ 656
  Motor........18, 483
Jamin and *Richard*, on theory of alternate currents........ 578
Jehl and *Rupp*, disk dynamo........ 480
Jehl, on continuous-current transformation........ 727

PAGE
Johnson & Phillips—Kapp's dynamos....................359, 403, 607
Transformers..705, 714
Johnson, on early dynamo.. 11
Joints in magnetic circuit....................................... 129
Joubert, on finding form of wave............................... 552
Method of exploring commutator.............................63, 65
On spurious resistance.. 89
On theory of alternate currents.............................. 573
On theory of dynamo... 20
Joule J. P., on back electromotive-force of motors.........486, 491
On electromagnet.. 143
On magnetic circuit... 115
Law of.. 493
Motors of... 483
Joule's researches.. 19
Journals... 328
Joyce, on heating of conductors................................ 376

K

Kapp, *Gisbert*—Alternators.........................552, 582, 607
Brush-holder.. 324
Commutator.. 315
On depth, &c., of winding..................................... 782
Dynamos... 402
Dynamo, calculations of....................................... 357
Efficiency of... 195
On dynamometry.. 755
On leakage in line.. 499
On limits of load... 386
On magnetic calculations...................................... 117
On magnetic circuit... 145
On method of driving core-disks............................... 292
On method of end-connecting................................... 307
On separation of losses....................................... 760
On size and output.. 109
On testing dynamos.. 759
On theory of dynamo... 21
On transmission of energy................................509, 740
Transformers...705, 714
On width of pole-faces.. 588
Kelvin, *Lord*—Alternators.................................16, 613
Disk dynamo... 479
On efficiency of motors....................................... 491
On theory of dynamo... 20
On theory of homopolar dynamo................................. 478

PAGE
Kelvin, Lord—
On transmission of energy.. 740
On wave winding..596, 613
Kennedy, A. B. W., test of combined plant 762
Kennedy, Rankine—Ironclad dynamo............................ 162
Alternators... 582
Polyphase motors.. 687
Kennelly on armature reaction 86
On reluctivity.. 144
Keys.. 337
Kingdon's inductor alternator................................. 640
Kohlrausch, on armature distortion............................ 69
On theory of alternate currents... 573
Curves showing armature reaction............................... 69
Kolben, Oerlikon dynamos..................................... 408
Koosen, on theory of alternate currents........................ 573
Investigations... 19

L

Ladd's self-exciting dynamo.................................. 14
Lag of current..558, 561
Effect on torque... 571
Lag effect of demagnetizing................................... 596
Lag, magnetic... 141
Lahmeyer—Dynamos..162, 441
On "far-leading" dynamos..................................... 725
Laminated series motors....................................... 693
Lamination of armature conductors.... ....91, 299, 342
Of armature core..............44, 91, 284, 451, 583, 609, 625, 673
Of pole-pieces..............................91, 602, 636, 643
Lamont, on electromagnet..... 143
Lap-winding...253, 279, 596
Lauckert's compound winding.................................. 57
Lauffen generator... 627
Lauffen transmission... 741
Laurence, Paris & Scott's motor generators...................... 724
Law of action and reaction...............................487, 516
Of efficiency of motor........ ....491, 493
Of hysteresis.. 137
Of Lenz.. 516
Of magnetic circuit......................................114, 145
Of maximum output of motor.................491, 494, 498, 656
Of Ohm... 23
Of transformer... 699

PAGE

Lead of current.... 558, 561, 564, 566
  Caused by synchronous motor.... 654
  Effect on field.... 596, 654
Lead of brushes.... 72, 76, 78, 85, 382, 448
  „ backward.... 395, 396
  „ in motor.... 514
" Leading " polar horn.... 76, 94, 382
Leakage in line.... 499
Leakage, magnetic.... 150
Leblanc (*see* Hutin and Leblanc)
Lecher, on homopolar induction.... 478
Ledeboer, on parallel running.... 766, 768
Leicester central station plant.... 622
Length and diameter of armatures.... 92, 342, 377
Length of conductor per volt.... 476, 622
Lenz, on dynamo as motor.... 18
  On electromagnet.... 143
  Law of.... 516
  Researches.... 19
Le Roux, on theory of dynamo.... 19
  On theory of alternate currents.... 573
Lightning arresters.... 774
Limit of armature current.... 381, 386
  In multipolars.... 396
Linde, on finding form of wave.... 552
Line, integral, of the magnetic forces.... 118
Lines—Magnetic.... 113
  Of force as distinguished from magnetic lines.... 114
  Of magnetic induction.... 120
Liverpool overhead-railway plant.... 545
Load on dynamo, limit of.... 381, 386
Locomotive motors.... 540, 545, 546
Lodge, Oliver J., on impedance.... 562
London Electric Wire Company's data.... 779
Lontin's machine.... 15, 43
Loomis, on the location of armature faults.... 775
Loss of power in magnetic cycle.... 135, 139
  In transformer.... 700, 715, 717
Losses, separation of.... 760
Lost amperes.... 190
Lost volts.... 180
  Calculation of.... 345
Lubrication of bearings.... 334, 619, 624
  Of commutator.... 771
Lubricators.... 334
Lummis-Paterson, on dynamo management.... 772

M

PAGE

Magnet coils, heating of........ 369
Magnets, forms of........ 158
Magnetic calculations........348, 356, 361
Magnetic circuit........114, 145
- Air gap in........ 128
- Joints in........ 129
- Branched........119, 150
- Calculations of........350, 356, 361, 364
- Reluctance of........119, 120

Magnetic—
- Conduction........ 118
- Creeping........ 141
- Cycle........ 134
- Field about conductors........24, 98
  - „ rotating........ 266
  - „ stiffness of........ 398
- Flux........114, 168
  - „ calculations of........ 348
- Leakage........ 150
  - „ allowance for........ 349
  - „ in asynchronous motors........ 681
  - „ measurement of........153, 752
  - „ in transformers........700, 704
- Lines........24, 28
- Permeability........120, 349
- Potential........116, 119
- Potential in gap........ 384
- Principles........ 112
- Properties of iron and steel........ 124
  - „ „ „ changes of........ 142
- Pull on armature........ 328
- Retardation in solid coils........ 141
- Shunt........ 530
- Units........112, 144

Magnetizing coil........ 117
Magnetizing current in transformer........698, 709, 715
Magnetization of armature........ 70
Magnetomotive-force........116, 117, 145
Magneto-electric machine........33, 48
- Theory of........ 179

Magneto-ringer........ 548
Magnolia metal........ 333
Main's alternators........ 624
Malderen's machine........ 10
Management of dynamos........765, 769

PAGE

“Manchester” dynamo 420
Manchester street station plant 625
Maquaire's regulator 745
Martin and *Wetzler*, on motors 484
Mascart and *Joubert*, on size and output 108
Mascart, on theory of dynamo 20
Masson's improvements 10
Mather, on armature compensation 389
Mather and Platt—Alternators 612
  Car motor 544
  Railway motor 545
  Dynamos 420
  Equalizers 726
Mavor and Coulson—Dynamos 438
  Mining motor 540
Maximum—Armature current 381, 386, 396
  Power of synchronous motor 655
  Values of sine functions 554, 564
Maxwell, J. Clerk, on self-exciting machines 19
  On self and mutual-induction 719
  On theory of alternate currents 563, 578
  On theory of transformers 721
Mean power, alternate-current 566, 571
Measurement of alternate-current power 567, 568, 571
  Of efficiency 758
  Of fluctuation of electromotive-force 178
  Of insulation resistance 752
  Of magnetic leakage 752
    ,, properties of iron 127
  Of power 753, 758
  Of resistance of armature 751
  Of total flux 178
Mechanical actions and reactions 96
Mechanical characteristics 502, 528
Mechanical points in design 327
Mesh connection of polyphase circuit 669
Menges, on armature compensation 391
  On dynamo testing 758
Meyer, on theory of dynamo 20
Meylan, on parellel running 766
Mild steel, magnetic properties of 123, 127
Minet, on dynamo tests 764
  On Edison dynamos 427
Mitis metal 127
Moncel (*see* Du Moncel)
Monophase motors 687

PAGE
Mordey, W. M., on alternate-current wave form.................. 718
  On alternator curve.................................. 558
  On armature exploration..............................64, 66
  On coupling compound dynamos......................... 767
  On finding form of wave.............................. 552
  On motor and dynamo analogies........................ 516
  On parallel working.................................. 21
  On the shunt motor.................................529, 530
  On slow changes in iron.............................. 142
  On synchronous motors................................ 653
  Alternators.. 619
  Inductor alternators................................. 641
  Method of cross-connecting........................... 276
  Methods of exploring commutator....................63, 66
  Multipolar ring...................................... 16
  Transformer..702, 714
  Victoria dynamo...................................... 417
Morin's dynamometer.................................. 756
Motors—Action of alternator............................ 571
  Alternate current (*see* Alternate-current motors)
  Asynchronous... 362
  Characteristics of................................... 505
  Commutation in....................................... 517
  Continuous current.................................482, 531
  Determination of windings............................ 527
  Direction of rotation................................ 517
  Efficiency of.................................487, 490, 498
  Historical notes..................................... 17
  Laminated.. 693
  Monophase.. 687
  Polyphase......................................21, 662, 678
  Pulsating.. 546
  Regulation of.. 519
  Reversal of..517, 518
  Rotatory-field....................................... 666
  Speed of...501, 503
  Theory of.. 492
  Torque of..501, 503
  For traction purposes................................ 540
Motor-generators....................................... 724
Mountain, W. C., commutator.......................... 322
Müller—Disk winding.................................. 279
  Method of measuring power............................ 757
  On electromagnet..................................... 143
  On magnetization of steel............................ 10
Multiphase (*see* Polyphase)

PAGE

Multiplex windings 272
Multipolar—Brush dynamo 457
Dynamos, design of 396, 580
Drum winding 265
Ring for alternators 581
„ windings 275
Polyphase plant 672
Murray's dynamometer 756
Tests of brush dynamo 458
Murray, on self-excitation 12
Mutual induction 94, 719

N

Negro (*see* Dal Negro)
Neumann, on laws of induction 19
On theory of alternate currents 573
Neutral point on armature shifted 70
Neutral points on commutator 77, 78, 257, 320, 515
Newall, on joints in magnetic circuit 129
Niagara plant 636
Niagara transmission 737
Niaudet, Alfred, on theory of dynamo 4
On gramme dynamos 401
Nickel, deposition of 784
Noise in running 777
Nollet's machine 10
Non-concentric poles 394
"Non-polar" dynamo 476

O

Oerlikon Co.—Alternators 627
Drum armature 307
Dynamos 408
Electro-metallurgical dynamos 472
Polyphase motors 678
Transformer 704, 706
Oerlikon works, transmission of power to 736
Ohm Dr. G. S., law of 23
Oil (*see* Lubrication).
As insulator 429, 705
Insulators 742
Open-coil armature 40
Advantages of 464
Open-coil dynamos 447

PAGE

Organs of dynamo ... 31
Oscillatory dynamo ... 16, 427
Output and size ... 102, 108
Output of alternators ... 589
Over compounding ... 237, 239, 728
Over-excited synchronous motor ... 654
Overload ... 786
Over-type, support of armature in ... 327

P

***Pacinotti*—Armature** ... 13, 14, 16, 41
    Disk dynamo ... 278, 479
    Motor ... 18
    Toothed core ... 286
***Page*—"Inductor" machine** ... 10
    Motor ... 18, 483
Paper (*see* Insulating Materials)
Parallel—Alternators in ... 647, 659
    Coupling machines in ... 766
***Paris and Scott's* method of end-connecting** ... 307
***Parker's* dynamo** ... 437
***Parshall's* multipolar dynamos** ... 434
***Parsons*—Turbo-alternators** ... 624
    Steam turbine, efficiency of ... 624 763
***Paterson and Cooper*—Core-disks and spider** ... 291
    Dynamos ... 439, 470
Pedestals ... 332
Peripheral speeds ... 109, 299, 367, 476
Period ... 549
Periodic governor ... 521
Periodicity ... 549
Permeability ... 120, 349
    Curves for iron and steel ... 125
Permissible heating ... 752
***Perry, John* (*see* Ayrton and Perry)**
    Ring winding ... 276
    Constant-speed motors ... 18
    On shaft stresses ... 321
    On theory of transformers ... 723
***Pescetto*, on size and output** ... 108
***Petrina's* machine** ... 8
***Peukert*, on armature reaction** ... 87
Phase of alternation ... 550, 555
Phase-difference ... 649
Phase-relation in transformers ... 708

PAGE

- Phase-splitting 689
- Phase transformation 731
- *Picou, R. V.*, on rotatory-field motors 21
  - On self-governing of motors 529
  - On synchronous motors 21, 652, 655
- Pitch 588
- *Pixii*, his machines 7
- "Phœnix" arc-light dynamo 465
  - Dynamo, particulars of 366
- *Plücker's* homopolar dynamo 475
- *Poggendorff*—Commutator 8
  - Investigations 19
- Polar-span, angle of 74, 387, 588
- Pole armatures 41, 584
- Pole-pieces—Eddy-currents in 92
  - Effect of shape on wave form 569
  - Lamination of 91, 602, 636, 643
  - Varieties of 393, 394
- Pole-faces, width of 588
- Pole surfaces, shaping of 68, 83, 95, 160, 388, 391, 393, 394, 471, 552
- *Pollak's* rectifying commutator 731
- *Polechko's* dynamo 481
- Polyphase and single-phase alternators 601
- Polyphase—Alternators 598
  - Motors 21, 662, 673
    - " history of 19
    - " theory of 21, 675
  - Transformers 718
- *Poncelet's* improvement of Prony brake 754
- Ponemah Cotton Mills plant 661
- Position of dynamo 769
- Potential at terminals 180
- Potential, magnetic 119
- *Potier*, on rotatory-field motors 21
- Power—Alternate-current 566, 571
  - Characteristic 200
  - Mean, of alternate currents 577
  - Measurement of 753
  - Of polyphase motors 676
  - Of synchronous motor 650, 652
  - Product of two factors 100, 493
- Power-factor of transformers 709
- Practical construction of armatures 284
- Pressure on bearings 327
- *Preston, T.*, on homopolar induction 478
- Prevention of sparking 80

PAGE
Primary and secondary currents ... 695
Products of periodic functions ... 557
Prony's brake ... 754
Puffer, on parallel running ... 766
Pulley, overhung ... 330
Pulsating motors ... 546
Pulsation ... 574
Pulvermacher's machine ... 8
Pyke and Harris's indicator alternator ... 642
Pyke and Salomons transformer ... 702

Q

QUADRATURE ... 557
Quarter phase ... 577

R

RACING of motors ... 519
Racking of armature conductors ... 185, 317, 572, 777
    Of connectors ... 317
Radian, unit angle ... 101, 173
Raffard's improvement of Gramme dynamo ... 400
    Of Prony brake ... 755
Railway, electric, machinery for ... 424, 448, 540
Ratio of transformation ... 697, 720, 727
Ravenshaw ... 434
    On dynamo testing ... 758
    Regulator ... 747
Raworth—Method of exploring commutator ... 66
    Coupling ... 338
Rayleigh, *Lord*, on alternate currents ... 578
    On dynamo testing ... 758
Reactance ... 560, 566
Reaction (*see* Armature reaction)
Reaction due to current in armature ... 58, 70, 382
Reaction—Mechanical ... 96, 317, 572
    Of inductance ... 559
    Of motor armature ... 510, 518
Reber, on polyphase motors ... 21
Rechniewski, on continuous-current transformation ... 727
    On size and output ... 109
Reckenzaun, on motors ... 582
Rectification of currents ... 38, 172, 449, 594, 728
Rectifying commutators ... 594, 728
Regulating dynamo, ways of ... 49, 51, 461, 743
Regulating resistance, specification of ... 785, 788

PAGE
Regulation of motors.................................... 519
 Of Parson's turbine.................................... 625
 Of Thomson-Houston dynamo.................................... 461
Regulators.................................... 748
Reignier, on regulators.................................... 748
Relation between size and output.................................... 340
Reluctance of magnetic circuit....................116, 118, 119, 120, 145
Reluctance, calculation of....................350, 356, 361, 364
Reluctivity, a lineal function of H.................................... 144
Remanence.................................... 132
Renshaw's spherical bearings....................333, 334
Residual magnetism.................................... 132
Resistance—Effect of, in rotor.................................... 681
 For regulating....................226, 445, 744, 747
 In characteristic.................................... 206
 Insulation.................................... 752
 Of coil, relation to size.................................... 377
 Of shunt coil.................................... 370
 Of wires.................................... 782
 Spurious, in armature.................................... 89
Resultant magnetic flux....................675, 678
Retardation of phase (*see* Lag)
 Of magnetism.................................... 141
Retarded field motors.................................... 693
Reversal of current in armature coils.................................... 80
 Of motor field.................................... 517
 Of polarity....................50, 469
Reversibility of dynamo.................................... 18
Reversing gear of motor.................................... 518
Rheostat as regulator....................226, 445, 744, 747
Rheostat, specification of.................................... 785
Rhodes, on synchronous motors....................21, 659
Richardson's governor.................................... 748
Right hand rule.................................... 22
Rimington, on alternate current-wave form.................................... 712
Ring armatures—Cross-connection of.................................... 276
 Winding of....................37, 40, 71, 251, 258, 275, 580
 Magnetization of.................................... 71
 For alternators.................................... 580
 Series connecting in.................................... 276
 Pacinotti's....................13, 14
 Gramme's.................................... 15
 Multipolar.................................... 275
Ritchie—His machines....................8, 10, 18, 483
 On magnetic circuit.................................... 115
Robin's disk dynamo.................................... 480

PAGE

- Rockers 78, 822
- Rocking of brushes 78, 771
- *Roessler*, on alternate-current wave form 718
- *Romilly*, on drum winding 15
- Rotatory magnetic field 662, 666
- Rotor 674, 668
  - In alternating field 688
  - Effect of resistance in 681
  - Of Stanley-Kelly motor 687
- *Rowland*, on relation between magnetomotive-force and flux 116
- *Rücker*, on limits of regulation 21, 242
- *Rupp*, on continuous-current transformation 727
  - Disc dynamo 480
- *Ryan, Prof. H. J.*,—Method of exploring commutator 66
  - On armature compensation 391
  - On synchronous motors 21
  - On transformer-current curves 711

S

- *Sahulka*, on alternate-current motors 21
- Salient poles 161
- Sandwiched coils in transformer 701
- Saturation, magnetic 121
  - In compound machine 232
- *Sawyer's* inductor dynamo 10
- *Saxton's* machine 8
  - Disk dynamo 479
- *Sayers*—Boosters 726
  - "Commutator" coils 394, 395
  - Dynamos 488
  - Electro-plating dynamo 471
  - Mining motor 540
  - On motor commutation 515
  - On parallel running 766
- *Schellen*, on theory of dynamo 4
- Schönenwerth plant 682
- *Schuckert & Co.*—Continuous-alternating transformer 781
  - Dynamos 440
- *Schültz*, on armature reaction 86
- *Scott and Mountain* 582
- Secondary and primary currents 695, 709
- "Section" of a winding 60
- Self-compensating armatures 394
- Self-exciting dynamo 49

PAGE
Self-exciting alternators.. 594
Self-governing motors.. 522
Self-induction.. 560
    Effect of, in synchronous running..650, 660
    In alternators.. 606
    In circuit with transformer.. 710
    Causes sparking.. 79
Self-oiling bearings.. 336
Self-starting synchronous motors.. 661
Sellers, Coleman—Designs for Niagara plant.. 636
    On double lubrication.. 335
Sellon, on continuous-current transformation.. 727
Separate coils for excitation.. 52
Separately-excited dynamo..48, 594
    Theory of.. 179
Separation of losses.. 760
Series-connecting in ring armatures.. 276
Series dynamo.. 49
    Characteristic of.. 197, 204
    Efficiency of.. 188
    Coupling of.. 765
Series lighting.. 445
Series motors—Characteristics of.. 506
    In transmission.. 509
Series-winding on motor.. 524
Series-winding not to be used with electro-plating dynamos........ 469
Shaft, design of.. 329
Shaping of pole-pieces...... ..68, 83, 95, 160, 388, 391, 393, 394, 471, 552
Shell-transformers.. 702
Short-circuits in armatures.. 773
Shunt coil calculation.. 372
    Heating of.. 370
Shunt current, calculation of..346, 370
Shunt dynamos.. 50
    Efficiency of.. 190
    Coupling of.. 765
Shunt motor—Characteristics of.. 510
    Constancy of speed.. 529
Shunt and series winding on motor.. 527
Siemens, Alexander, on torque of motors.. 508
    On shunt dynamo.. 211
Siemens, Sir William—Efficiency of motors.. 491
    Early researches..11, 16
    On transmission of power..490, 510
    On shunt dynamo.. 210
    On compound winding.. 57

PAGE
Siemens, Werner von—Self-exciting dynamo........ 13
On armature reaction........ 86
Mining drill........ 546
Shuttle-wound armature........11, 33, 469
Invents name of dynamo........ 13
On transmission of power........ 491
Siemens—Alternating-continuous transformers........ 728
Alternators........ 609
Dynamo (old)........15, 33, 158, 469
Dynamo (new)........ 404
,, characteristics of........196, 201, 211
,, efficiency of........ 195
Homopolar dynamo........ 475
Mining drill........ 546
On efficiency of motors........491, 492
Law of........ 498
Winding........ 303
Siemens and Halske—Alternators........ 609
Brush-holder........ 325
Dynamos........163, 302, 367, 397, 406
Electro-plating dynamos........ 469
Ring dynamo........ 163
Silver, deposition of........ 783
Silver solder........305, 610
Sine curve........37, 62, 548, 550, 553, 569, 713
Sine-curve controversy........553, 569, 713
Single-phase motors........ 687
Sinsteden—Self-exciting dynamo........ 10
On theory of dynamo........ 19
Size of dynamo in relation to output........108, 340, 377
Size and output in relation to cooling surface........ 376
Skin-effect........ 578
Slater Lewis' regulator........ 745
Sleeve for armature........292, 332
Sliding contacts........5, 35, 312, 326, 334, 475, 585, 630, 673
Sliding rails........ 769
Slip in asynchronous motors........666, 675, 678, 679, 681
Slip in monophase motors........688, 691
Slip-rings (*see* Sliding contacts)
Slotted armature........ 343
Smith, Rev. F. J.—Method of measuring torque........ 185
On work-measuring machines........755, 756
Smith, Holroyd, his brush........ 321
Smith, Willoughby, on homopolar dynamo........ 476
Snell—Motors........ 533
On horse-power of motors........ 531

PAGE
Snell, on size and output ... 386
South London Electric Railway plant ... 424
Spacing in armature winding ... 246, 256
Sparking—Causes of ... 78, 381, 450, 771
  Prevention of ... 80, 381, 387, 397, 450, 514, 771
Specification of alternators ... 787
  Of dynamos ... 785
  Of transformer ... 789
Specific utilization of copper ... 368
Speed—Dependence of volts on ... 21, 45, 173, 346, 476, 549
  Advantage of high ... 47, 369
  Peripheral ... 109, 299, 367, 476
  Regulation of shunt motor ... 511
  Relation of, to characteristic ... 205
  (*See also* Critical speed *and* Slip)
Sperry's arc-light dynamo ... 465
Spherical armature ... 458
Spherical bearings ... 334, 434, 628
Spiders ... 290, 332
Spiral winding ... 596
Split-phase motors ... 689
Splitting the phase ... 689
Sprague, F. J.—Motors ... 534, 536
  On motor regulation ... 522
Spurious resistance ... 89
Square-root of-mean-square ... 554
Squirrel-cage rotor ... 667
Stafford and Eaves' electro-plating dynamo ... 470
Staggered poles ... 686
Stampings for cores ... 286, 583, 674, 702
Stanley's constant-current alternators ... 640
Stanley-Kelly—Inductor alternators ... 641
  Two-phase motor ... 686
Star connection of polyphase circuit ... 669
Starting—Dynamo ... 769
  Of motors ... 509
  Torque of asynchronous ... 680
Stator ... 668, 674
Statter's arc-light dynamo ... 465
Steam consumption, test of ... 762
Steel, magnetic properties of ... 128, 134
Steinmetz, on alternate-current wave form ... 712
  On asynchronous motors ... 685
  On polyphase motors ... 21
  On loss by hysteresis ... 137
  On synchronous motor ... 21, 659

PAGE
Step up transformers..694, 737
Stiffness of field..398
Stohrer—Disk dynamo..479
    Machine..8
Storch, on size and output..109
Stranded copper conductors..299
Stray field..150, 152
Stray power..106, 758
Street-tramway generator..483
Stress, effects of, on magnetism..294
Stresses in shaft..331
Stroh, A., constructs self-exciting dynamo..13
Stromberg, on armature reaction..86
Sturgeon—Machine and commutator..8, 33
    On magnetic circuit..115
    Wheel..483
Summation of electromotive-forces..591
Sunk windings..284, 286
Surface of heat emission..373
Surface windings..284
Swinburne, James, on armature exploration..64
    On armature reaction..382
    On armature compensation..389
    Dynamo designs..262
    On dynamo testing..758
    Method of end connecting..307
        „ exploring commutator..63
    Transformers..707, 714, 717
Synchronizer..659
Synchronizing alternators..659
Synchronous motors..21, 647
    Variation of excitation of..652, 656
Synchronous polyphase motors..660
Symbols, table of..169

T

TABLES—Of binding wires of Edison dynamos..297
    Of circuits of Brush dynamo..456
        „ Thomson-Houston dynamo..462
    Of constant-speed generator and motor compared..528
    Of cross-sections for different shapes..378
    Of current and volts of Siemens' machine..108
    Of data of A. E. G. motor..538
        „ of Croker and Wheeler's motors..538
        „ of Edison dynamo..430, 431

PAGE

Tables—
  Of data of Edison-Hopkinson dynamo...................... 354
    ,, of Elwell-Parker continuous-current transformer... 725
    ,, of Kapp dynamo.........................357, 358, 363
    ,, of Sprague motors...................................... 535
    ,, of Westinghouse Co.'s street-car motors............ 543
  Of effect of joints in wrought iron......................... 130
  Of efficiency test of Goolden-Willans plant.................. 436
    ,, ,, Snell motor............................ 533
  Of electro-metallurgical data............................783, 784
  Of flux-densities in dynamos................................ 368
  Of flux through various parts of Lahmeyer's dynamo........ 153
  Of heat waste at different current-densities.............. 371
  Of hysteretic constants...................................... 137
  Of hysteresis waste.. 140
  Of journal sizes... 330
  Of leakage coefficients...................................... 151
  Of motor speeds and currents................................. 488
    ,, torque and currents.................................. 507
  Of pole width of alternators................................. 589
  Of shunt-motor speeds.. 529
  Of symbols... 169
  Of transformer data.. 714
    ,, relations..................................... 720
  Of triplex two-pole drum winding 274
  Of values of B, μ and H in iron.......................... 126
  Of winding of Lauffen three-phasers.......................... 629
    ,, on Siemen's plan................................. 260
  Of two-pole drum winding..................................... 247
  Of two-pole symmetrical winding.............................. 265
  Of four-pole drum-winding.................................... 269
  Of eight-pole drum winding................................... 268
  Of lap winding... 255
  Of wave winding.. 255
  Wire gauge and amperage..................................780, 783
Tape (*see* Insulation)
Tatham, on dynamometry... 756
Teazer coils...56, 451
Teeth of armature cores..........................14, 43, 99, 287, 343, 602
  Produce eddies in pole-pieces................................ 98
Temperature rise (*see* Heating).
Terminal potential difference.................................... 202
Tesla, Nikola—High frequency.................................. 570
  On polyphase work.. 665
  Split-phase motors... 689
  Two-phase motor.. 671

PAGE
Testing dynamos......751, 763
  Specification of......787, 789
Testing—For faults in armature......752, 773
  Insulation resistance...... 752
  Temperature-rise...... 752
Tests of car motor...... 542
Theory of compound-wound motors...... 522
  Of continuous-current transformation...... 727
  Of dynamo......19, 22, 45, 168
    „ alternate current...... 578
    „ series wound...... 188
    „ shunt wound...... 190
    „ compound wound...... 224
  Of electric motive power...... 489
  Of monophase motors...... 690
  Of polyphase motors...... 675
  Of the synchronous motor...... 648
  Of transformer......699, 708, 719
Thickness of core-disks...... 284
Third brush for shunt coil...... 52
Thompson, M. E., on armature distortion...... 69
Thompson, S. P., on armature exploration...... 63
  Method of compensating armature...... 390
Thomson, Elihu, on armature compensation......389, 391
  On breadth of alternator coils...... 590
  On continuous-current transformation...... 727
  On dynamometric governing...... 749
  Experiments with alternating current...... 687
  His inductor...... 642
  His open-coil dynamo...... 16
  On transformer conductors...... 717
  On constant-current transformers...... 717
Thomson-Houston—Dynamo...... 458
  Transformer...... 714
Thompson, James, on brake dynamometer...... 755
Thompson, Joseph J., on joints in magnetic circuit...... 129
  On skin-effect...... 578
Three-dynamometer method...... 568
Three-phase alternators......599, 604, 627, 644
    „ convertable to single phase...... 636
  Combinations...... 664
  Currents......600, 665, 670
  Inductor alternator...... 644
Three-voltmeter method...... 568
Three-wire system, transformers for...... 718
Thrust bearings...... 333

PAGE
Thurston, on Brush dynamo.. 458
Thury—Continuous-current machines for transmission............. 736
  Dynamos.. 442
  Inductor alternators................................. 646
  Regulator................ 745
Timmermann, A. H. and C. E., on radiation of heat.............. 376
Tooth (*see* Teeth).
Torque of alternators...................................... 571
  Of armature............... ....96, 100, 102
  Constant.. 749
  Of asynchronous motors..........................676, 681, 685
  Of monophase motors.. 691
  Of motors.......... ....501, 503
  Of synchronous motor.. 650
Traction motors..540, 545, 546
"Trailing" polar horn......................................76, 94, 382
Tramway generators 433
Transformers.. 694
  Construction of.. 700
  Continuous-current........... 724
  Design of.. 715
  For constant current........ · 717
  For insulation tests.. .. 752
  Modern types.. 702
  Polyphase.. 718
  For three-wire systems....................................... 716
  Specification of... 789
Transformer-action of polyphase motor 676
Transformer-cases, specification of............................ 790
Transmission dynamometer.................... 755
Transmission of energy....................... 732
  At high voltage.. 694
  By alternate currents.................................647, 651
  By polyphase currents.. 668
  Two-series motors in... 509
Triplex-winding..273, 274
Trotter, A. P., on magnetic leakage............................ 158
  On motor regulation... 530
  Regulator... 747
True watts.. 567
Turbo-alternator.. 625
Two-phase—Alternators......................................599, 634
  Combinations...663, 670
  Currents.. 600
  Motors....................................661, 666, 671, 673, 686
"Tyne" dynamo brush-holder.................................... 322

U

PAGE

Under-type, support of armature in 327
Unipolar dynamo 6, 475
Units, connections between 101
Units, magnetic 112, 144
Unwin, on brake dynamometer 755
Uppenborn, on compound winding 242
    On homopolar dynamos 477
Useful points in designing 367, 581, 588, 678, 702, 715
Utilization of copper, specific 368

V

Van Malderen's machine 10
Varley, Cromwell F. 174, 701
    His transformer 701
Varley C., and *S. A.*, self-exciting machine 12
Varley, S. Alfred, on compound winding 56
    On homopolar dynamo 475
    His machines 12
Varley, F. H., his machine 12
Varley, O., his machine 12
Ventilation of armatures ... 164, 292, 295, 378, 396, 403, 420, 452, 616, 628
    Of field-magnets 378
    Of transformers 708, 716, 717
Vertical-shaft dynamo 412
Vibration and noise 295, 777
"Victoria" dynamo 276, 285, 417
Vincent's multipolar drum 16
Virtual volts and amperes 553, 564
Voltage required in deposition 784
Volts lost in the armature 180
Volts, virtual 554
Volume of magnetizing coil 371
Volume (*see* Output).
Vulcanized fibre (*see* Insulating Materials).

W

Walenn, on reversibility of dynamo 18
Waltenhofen, on theory of dynamo 20
Warburg, on loss per magnetic cycle 135
Wasted power—In copper 347, 371, 761
    In iron 137, 140, 347, 761
Waste of power at different current-densities 371
Waterhouse's regulator 747

PAGE

- *Watkins*, his machine ... 8
- Watt, the ... 200
- Wattless current ... 567
- Wattmeter ... 568
- Wave form (*and see* Sine curve) ... 549, 552
  - Of transformer currents ... 712
- Wave winding ... 596
- *Webber*, on motor generators at Chelsea ... 725
- *Weber*, on laws of induction ... 19
  - On theory of alternate currents ... 573
  - On unipolar induction ... 475, 478
- *Weber, H. F.*, on Lauffen transmission ... 742
- Weber, the ... 144
- *Wedding*, on alternate-current wave form ... 712
- Weight of dynamos (*see also* Output), 405, 412, 416, 426, 429, 438, 444, 626
  - Of copper ... 416, 626
- *Weisbach*, on power-measuring machines ... 755
- *Wensteröm*—Dynamo test of ... 764
  - Pierced core-disks ... 290
- *Westinghouse Co.*—Air-blast for cleaning ... 771
  - Alternator ... 583, 602, 626, 638
  - Core-disks ... 288
  - Niagara alternators ... 688
  - Street-car motors ... 542, 544
  - Transformer ... 703, 714, 717
- *Weston's* dynamos ... 16, 160
- *Wheatstone, Sir Charles*—Motor ... 18
  - On self-exciting dynamo ... 13
  - Machines ... 9, 10
  - Use of electromagnets ... 9
- Wheel dynamo ... 479
- *Wheeler*, on parallel running ... 766
- Whirls of magnetic lines ... 26
- Widening of gap-space ... 379
- Width of pole-faces (*see* Pole-pieces)
- *Wiener's* data ... 339
- *Wilde's* Alternator ... 580
  - Dynamos ... 10, 11, 16, 48, 469
- *Willan's* Governor ... 748
  - High-speed engines ... 426, 434
- Willesden paper (*see* Insulating materials).
- *Wilson*, on retardation of magnetism ... 142
- Winding of alternators ... 596
  - Of armatures ... 297
  - Of field-magnets ... 372, 607, 611, 621
  - Of Lauffen generator ... 680

PAGE

Winding of alternators—
  Of multiplex armatures.................................... 272
  Of polyphase motors................................667, 673, 686
  Tables..........................247, 255, 260, 265, 268, 269, 629
  Of transformers......................................700, 715
  Relation of, to characteristic............................ 207
  Triplex..273, 274
Wires (*see also* Binding wires *and* Cores)........................ 776
Wire-wound armatures.. 298
Worms de Romilly, on drum winding............................ 15
Wood's arc-light dynamo...................................... 465
Wood (*see* also Insulating materials)
  For distance pieces................................286, 304, 307
  For wedges.. 602
  For driving horns... 296
Woolrich's machine...8, 469
Work done by conductor in field..............................104, 486
  By motor...496, 501

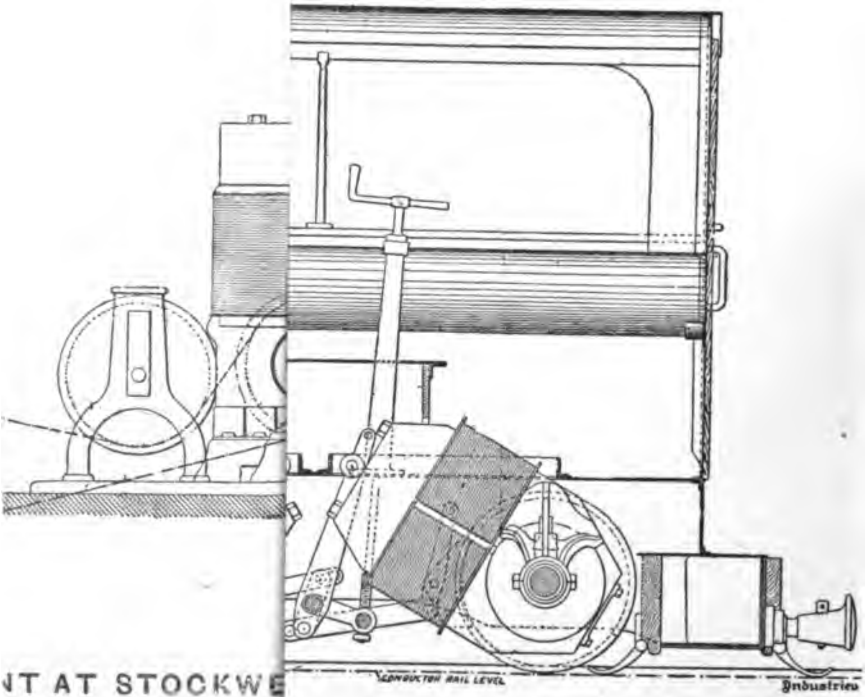
Z

ZEUNER'S valve-gear diagram.................................. 551
Zickler, on compound winding.................................. 242
Zinc—Cost of, for motive power................................. 485
  Use of, for footsteps..............................152, 354, 425
    " coil frames.. 612
Zipernowsky's Alternator.....................................584, 611
  Transformer... 702

Plate ix

Y· PLANT OF T

5 HP. AT 100 REVS. PE



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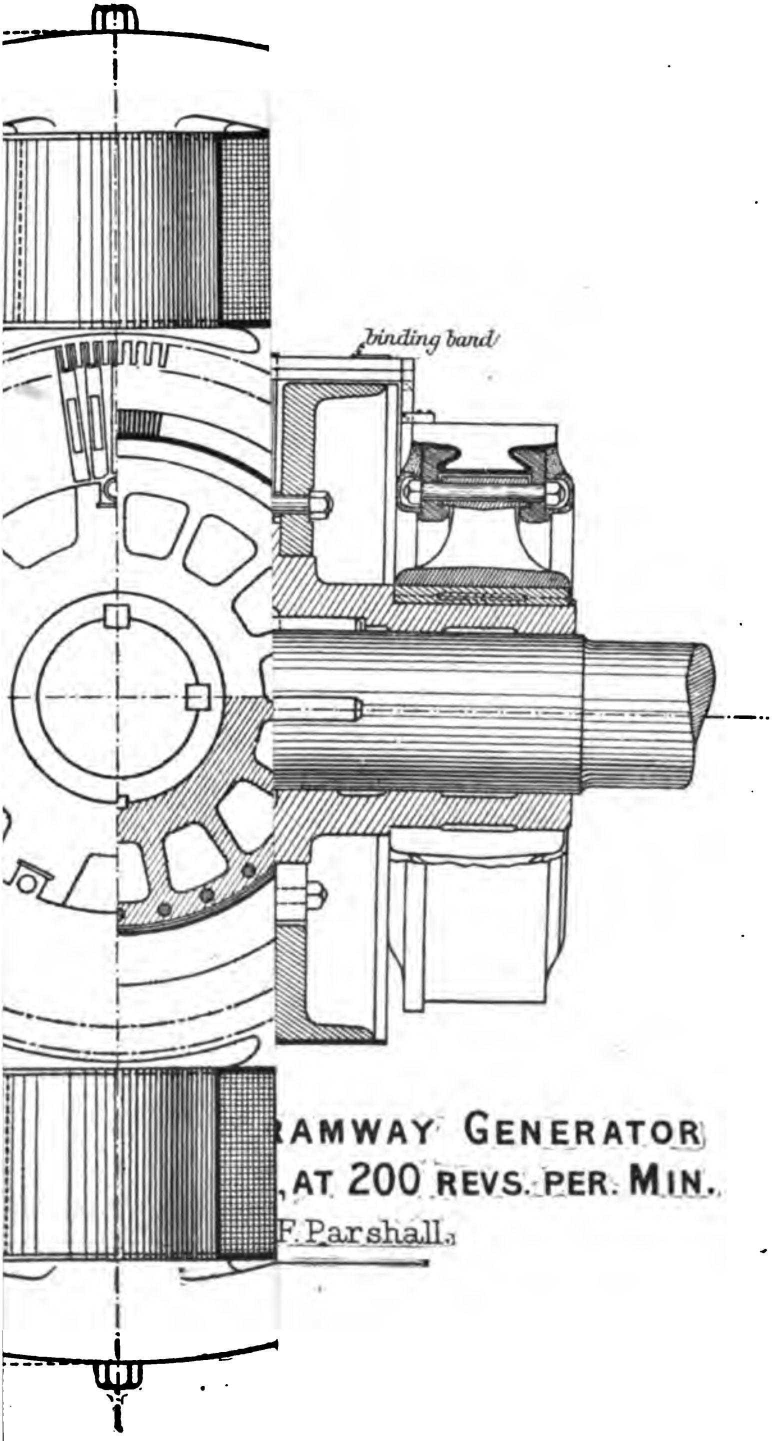


RAMWAY GENERATOR

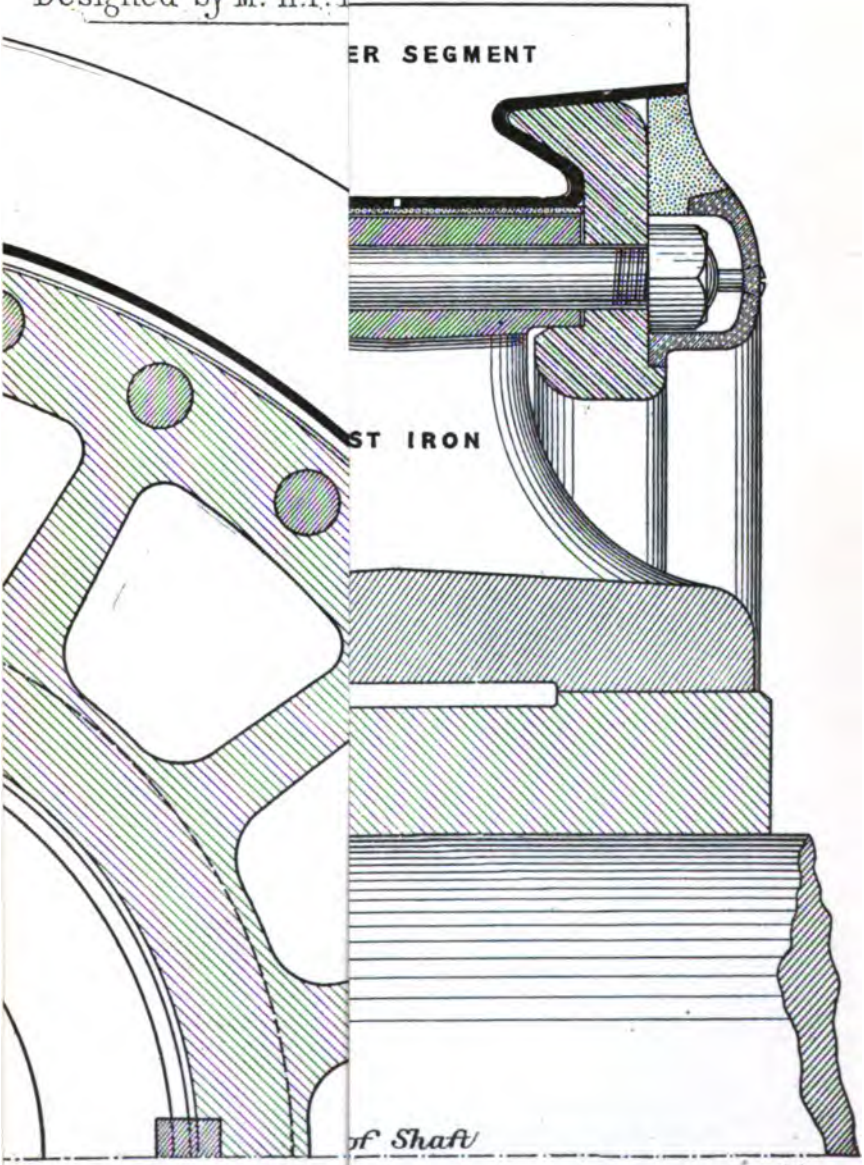
, AT 200 REVS. PER. MIN.

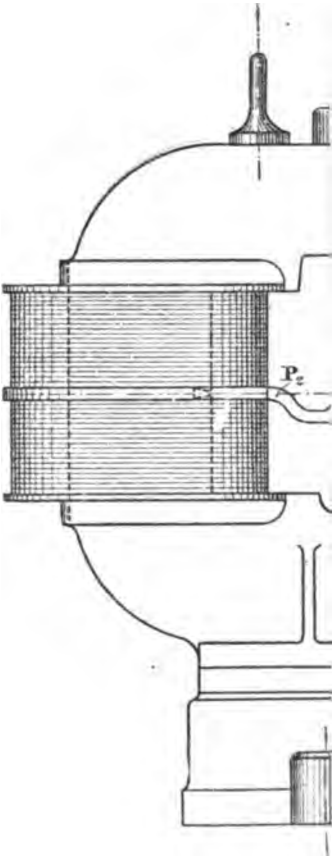
F. Parshall.

Plate xi

REET—TRAMWAY
AMPERES AT

Designed by Mr. H.F.





TRANSMISSION

0 REVOLUTIONS PER MINI

Coulson.

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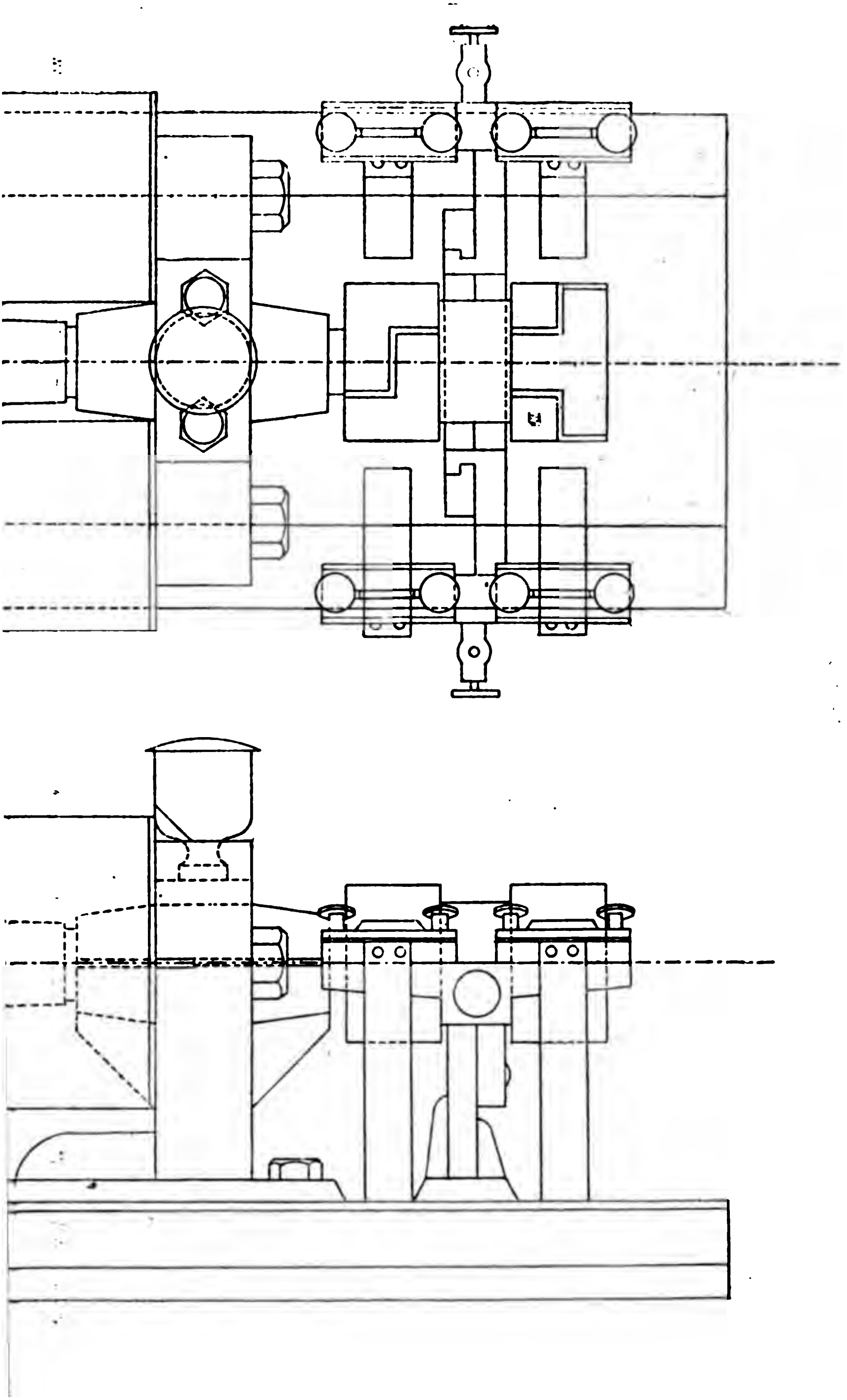
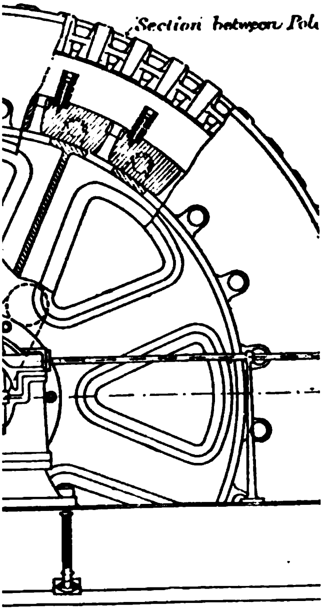
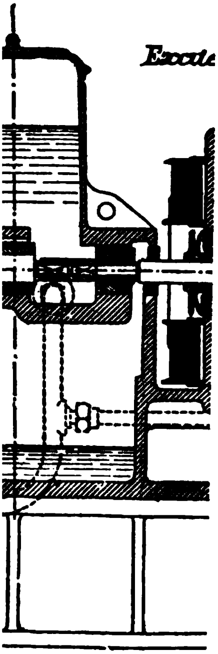


RNATOR;
PERES AT 2000 V
R MINUTE.
Engineering Comp

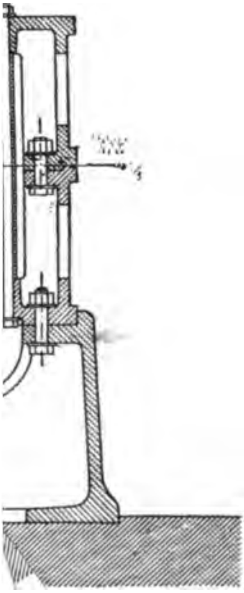


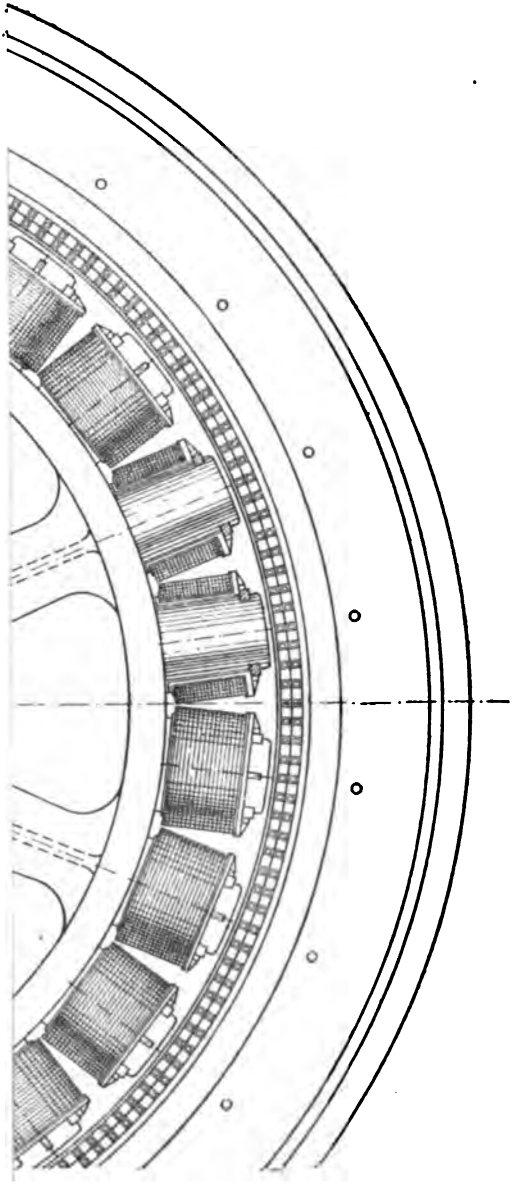

Excite

FOR 5000

by Mr C E

Scale





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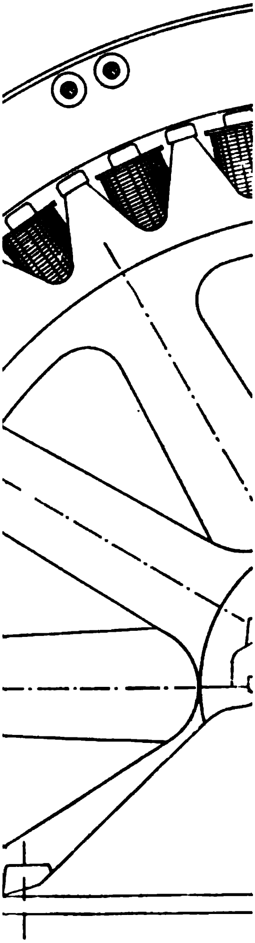

own, Boveri & Co.

Plate xviii

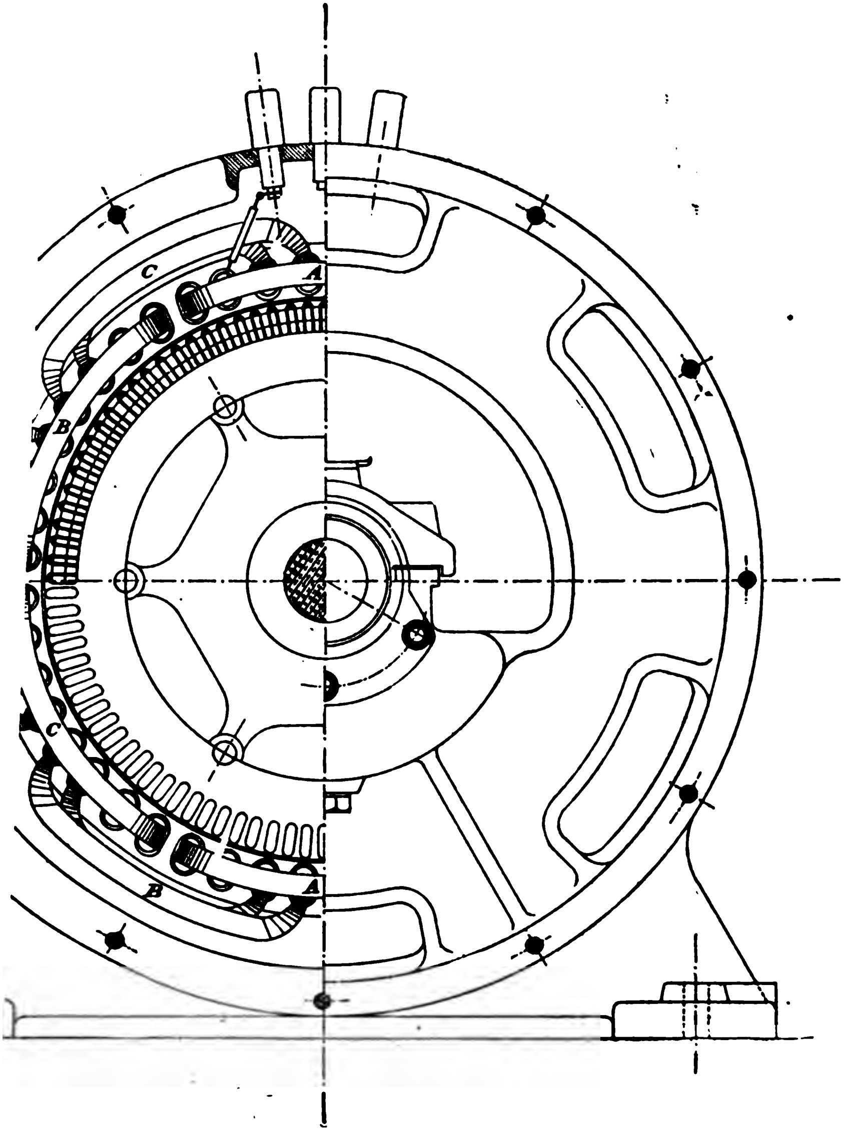

Plate xix

TRANSFORMER

Designed by G. Knapp

Constructed by Messrs. Johnson and Phillips